Sediment budget for a North Pennine upland reservoir catchment, UK

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SEDIMENT BUDGET FOR A NORTH PENNINE UPLAND RESERVOIR CATCHMENT, UK

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This thesis is submitted in accordance with the regulations for the degree of Doctor of Philosophy in the University of Durham, Department of Geography, 2003

Declaration

I confirm that no part of the material presented in this thesis has previously been submitted by me or any other person for a degree in this or any other university. In all cases, where it is relevant, material from the work of others has been acknowledged.

Signed: V. Halliday

Date: 15/12/03.

ABSTRACT

Sediment delivery from upland fluvial systems in the UK is of considerable importance in catchment management. However, scarcity of detailed data on sediment sources, storage and linkages between geomorphic processes inhibits current understanding of such systems. A sediment budget for an un-gauged, upland catchment at Burnhope Reservoir (North Pennines, UK) has been developed that couples catchment sediment sources and suspended sediment dynamics to reservoir sedimentation and; quantifies historic and contemporary sediment yields.

Stream-side scars and cut banks are the dominant catchment sediment sources with greatest connectivity in first order tributaries during high discharge events. The catchment sediment system is supply-limited and sediment exhaustion occurs on an intra and inter-storm event basis. Bathymetric surveys, core transects and aerial photographs were used to assess spatial variability in sediment accumulation in the reservoir. Physical and radiometric analysis (^{137}Cs) of core sediments provided estimates of dry bulk density, particle size variations and a sedimentation chronology. Total reservoir sedimentation over the 67 year period has been estimated at 592 t yr^{-1} ± 10% (33.3 t km^{-2} yr^{-1}) with average sedimentation rates of 1.24 and 0.77cm yr^{-1}, calculated from the distal and proximal areas of the reservoir respectively. Inputs of fine suspended sediment from direct catchwater streams accounts for 54% of sediment supply to the reservoir (best estimate yield of 318 t yr^{-1} ± 129%), while inputs from the actively eroding reservoir slopes and shorelines contribute a gross yield of 328 t yr^{-1} ± 92%. However, 70% of sediment from shoreline erosion is >2 mm diameter and is stored on the shoreline and toe slopes. The remaining 30% (98.4 t) of fine sediment is transferred to deep-water reservoir storage. This highlights the importance of shoreline erosion and sediment storage in the overall budget. Error analysis of the sediment balance equation enabled the residual sediment inputs from ungauged tributary streams to be estimated (232.6 t yr^{-1}± 394.9%). The specific sediment yield of 33.3 t km^{-2} yr^{-1} to Burnhope Reservoir is relatively low. It is 40% lower than the average yield of 84 t km^{-2} yr^{-1} estimated from British storage reservoirs (DETR, 2001) and an order of magnitude lower than estimates from South Pennine reservoirs.

Analysis of the particle size of core sediments showed abrupt increases in sand-sized particles in the top 20 cm of the cores (late 1970s onwards). This is related to the diverging trends in winter and summer-centred rainfall records and rapidly fluctuating reservoir levels. The sediment budget approach together with the chronology of reservoir sedimentation identifies the main sediment transfer pathways in the Burnhope catchment, and provides evidence of both extrinsic and intrinsic controls on sediment transfer and deposition.

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This thesis forms part of a wider EU funded research project (ENV4-CT98-0789) investigating Water Resource Management in a Changing Environment (WARMICE). I would therefore like to extend my thanks to Dr Sue White for securing the funding for this project.

The fieldwork for this thesis was based at Burnhope Reservoir in Weardale, North Pennines. This was carried out in collaboration with Northumbrian Water Limited (NWL) and was only possible through the kind permission of a number of farmers (Robert Walton, Dennis Rutherford) and landowners (Steve Cattlan). Special thanks go to Alec Piert, a farmer who's interest in geomorphology and local knowledge of the study catchments provided valuable insight into farming practices and recent land use change. Fond thanks go to the employees of Wearhead Water Treatment Works who could always be relied upon for support in the field, sending search parties to rescue departmental vehicles from dirt tracks when things got icy! Particular thanks go to Jim Prentice and Dave Pattinson for supplying data on reservoir operations, maps and photographs of Burnhope Reservoir.

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CHAPTER 1 - INTRODUCTION AND SCOPE OF RESEARCH

1.1 Introduction

Erosion of the British uplands is an issue of immediate concern (DEFRA, 2001; McHugh *et al.*, 2002) but has received little attention in the geomorphic literature (Warburton *et al.*, 2003). This is compounded by a serious lack of detailed data on the rates and extent of upland erosion (McHugh *et al.*, 2002). It is therefore difficult to assess erosional patterns, especially the ability to distinguish between natural and human driven processes and between contemporary and historical degradation (Warburton, 1998). A recently completed research project by the Ministry of Agriculture, Fisheries and Food (MAFF, 1999) has shown that the activities of humans and grazing animals are the principal causes of new and continued erosion in upland Britain. Recent EU and MAFF initiatives to preserve upland environments and habitats mean that upland erosion must be understood, and in areas where erosion is already occurring, managed effectively. Sedimentation in reservoirs is often a consequence of erosion in upland catchments. The recent report by The Department of the Environment, Transport and the Regions (DETR) on Sedimentation in British Storage Reservoirs (2001) provides the first comprehensive study on reservoir sedimentation in the UK. The report has highlighted the issue of loss of capacity in British reservoirs and the environmental consequences of reservoir sedimentation, predicting a mean loss of storage of 3% over the next 20 years (DETR, 2001). This prediction does not account for the uncertainties in erosion as a result of future climate change and shifting land use practices.

There is growing recognition of the impact of land use change on upland erosion in terms of stocking densities of sheep and artificial land drainage (gripping). The main pressures on upland habitats are heavy livestock grazing (often made worse by the uncoordinated management of common land), inappropriate management of some grouse moors, increased recreation, climate change and atmospheric pollution (English Nature, 2001). Currently over half of England's Statutory Sites of Scientific Interest (SSSI) rely on grazing as an essential form of management, but English Nature's seventh annual report reveals that overgrazing accounted for 87% of all recorded damage to SSSI's between April 1997 and March 1998. English Nature's proposal for Common Agricultural Policy (CAP) reform based on Agenda 2000 is geared towards eliminating overstocking of sheep and the consequent overgrazing that is enhancing upland erosion. A £4.5 million project funded by the Ministry of Agriculture and

European sources has been launched to improve heather moorland management in the Northern Uplands to reduce potential erosion. This project offers grants for reducing sheep numbers and restoring natural upland drainage by blocking grips. The recent outbreak of Foot and Mouth Disease in the uplands has resulted in re-evaluation of how farmland and moorland are managed. Restocking of livestock farms affected by the disease could provide a chance to evaluate the sustainability of grazing systems.

Effective management of upland regions requires knowledge of the location and rate of erosion in terms of sediment supply, transfer and deposition. Sediment delivery and deposition in upland regions has important implications for catchment management in terms of water quality and supply. Sedimentation within reservoirs has been identified as a major problem in many parts of Europe resulting in the reduction of available water storage, blocking of outlet sluices and damage to expensive power generation machinery (Mahmood, 1987; White *et al.*, 1996a). In addition to loss of capacity and interference in reservoir operations, periods of enhanced sediment delivery in fluvial systems can lead to increased turbidity that alters water colour and reduces the quality of water. Sediment can carry chemical pollutants such as nutrients, pesticides and heavy metals as well as biological contaminants such as bacteria and viruses (Marks and Rutt, 1997) thus increasing environmental damage and water treatment costs. The influx of organic sediments is of particular concern in the water treatment purification process as increased pollutant levels (bromide and nitrate) in reservoir waters contaminate drinking water (Marks and Rutt, 1997).

The sediment budget approach provides a robust methodology for determining reliable estimates of erosion and deposition and providing an overall indication of how upland sediment systems operate in terms of the relative significance of slope and channel processes (Dietrich and Dunne, 1978; Duijsings, 1987; Reid and Dunne, 1996; Warburton, 1998; Warburton *et al.*, 2003). Development of a series of strategically placed sediment budgets throughout upland regions in England and Wales has been suggested as a method of understanding soil erosion across a range of different upland environments (Warburton *et al.*, 2003).

A useful recent example that exemplifies this approach is from Catcleugh Reservoir, Northumberland. A report prepared for Northumbrian Water Ltd by Warburton (2003) reviews an episode of fine sediment contamination of raw water in relation to a heavy rainfall event and rapid infilling of the reservoir that occurred in August 2002. A stream reconnaissance survey of the major tributary streams feeding Catcleugh Reservoir revealed that slope failures were the main sources of fine sediment in the catchment.

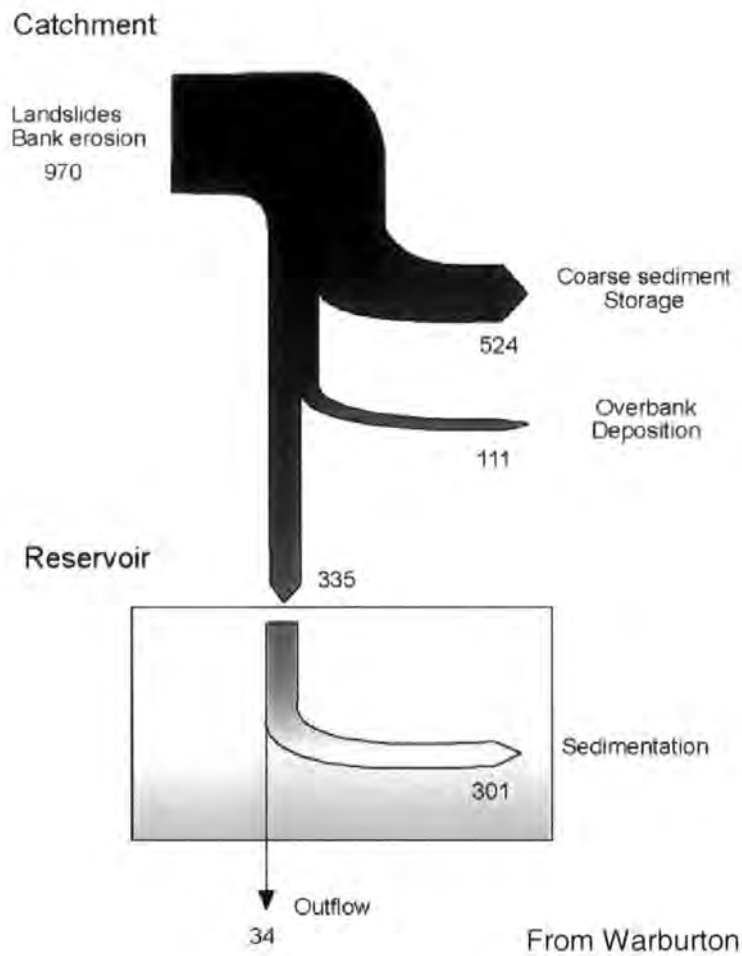
A lack of fine sediment storage noted at the base of the failures and the steep stream gradients of the tributaries lead to the assumption that the majority of fine sediment supplied during the event had been delivered to the reservoir as a major sediment plume. Figure 1.1 quantifies sediment transfer to Catcleugh Reservoir using proportional arrows in a sediment budget framework. In this model the sources and stores of sediment have been identified and the linkages between catchment supply and sediment transfer evaluated. A second storm event in October 2002 resulted in failure of raw water quality once again and this was attributed to sediment supply from the erosion scars left after the August flood that remained closely linked to the stream channel. As future climate change predictions suggest increasing potential hazard to reservoir water supply due to increased storminess in upland Britain (Warburton, 2003), a need for further research into sediment supply to storage reservoirs is evident.

This example from Catcleugh Reservoir emphasises the advantages of using sediment budgets to identify sediment transfer pathways and quantify sediment loads. Other general advantages of the sediment budget approach (Reid and Dunne, 1996) include:

(1) flexibility, as budgets may be constructed for any of several steps in the production and transport of sediment in a watershed.
(2) adaptability, as the technique can be used to describe existing patterns of sediment transport and production in a watershed and can also be used to predict changes in sediment regime, and
(3) identification of erosion processes, their controls and estimates of their rates, provides information used to target processes for which monitoring will be most useful.

In order to address the issues of sediment transfer and reservoir sedimentation in contrasting upland catchments of Europe, an EU funded project 'Water resources management in a changing environment' (WARMICE) was initiated in 1999. The WARMICE project formed part of the EC Environment and Climate Programme (Framework IV) and aimed to develop methodologies for assessing the impacts of changing land use and climate on flow patterns and associated sediment supply and transport in upland regions of the UK, Spain and Austria. Three contrasting focus areas were chosen for the study including Burnhope Reservoir on the River Wear in northeast England, the Yesa Reservoir on the river Aragón in the Spanish Pyrenees and the Sölk Reservoir on the Sölk River in the Austrian Alps. Gaining a better understanding of the sediment delivery processes and hydrological functioning of these catchments under current conditions was a prerequisite for predicting catchment response to future climate and land use change scenarios. The principal role of the UK

Figure 1.1 Sediment budget identifying sediment transfer pathways and quantifying sediment loads (tonnes) from the Cattlehope Burn catchment to Catcleugh Reservoir, Northumberland during a major storm event occurring in August 2002.



From Warburton (2003)

based research group was to document and investigate sediment delivery processes in the upland catchments feeding Burnhope Reservoir and relate these processes to hydrological events and the archive of sediment stored in the catchments (principally reservoirs and floodplains). The emphasis was on (1) field mapping and monitoring to develop a dataset of sediment yields and discharge for previously ungauged catchments, (2) reservoir coring and (3) integration of the these two elements into a sediment budget model of the catchment reservoir.

This thesis is part of the UK-based branch of the WARMICE project that is funded by the European Commission. This thesis is concerned with developing a reservoir sediment budget combining estimates of contemporary and long-term sediment yields from stream monitoring and reservoir sedimentation respectively. The majority of past research into sediment transfer in upland regions has focussed on estimating sediment output from catchments over short-term contemporary timescales (Stott *et al.*, 1986; Moore and Newson, 1986; Francis and Taylor, 1989) and on reconstructing sediment transfer over long-term periods from sediment stored in the catchment (floodplains and reservoirs) (Labadz, 1988; Duck and McManus, 1990, 1994; Hutchinson, 1995; Labadz *et al.*, 1995; White *et al.*, 1996a; van der Post *et al.*, 1997; Foster and Lees, 1999a & b). The research has concentrated on quantifying sediment output from disturbed catchments with a history of land-use change to assess the response of sediment delivery to the onset or intensification of forestry and farming practices. Due to the focus on catchments disturbed by human activity it is often difficult to isolate the potential influence of climate change on sediment delivery in upland catchments. As a result few studies have assessed the potential effects of climate change on sediment transfer in upland catchments. There have been few studies of sediment transfer in upland catchments of the UK that have adopted a sediment budget approach to identify and quantify sources and stores of sediment and evaluate the temporal scales of coupling between the key budget components (Stott *et al.*, 1986; Walling *et al.*, 1998; Evans and Warburton, 2001; Johnson and Warburton, 2002). This investigation is one of the first to evaluate the temporal and spatial aspects of sediment transfer in North Pennine catchments through assessment of sources and stores of sediment using a sediment budget framework.

1.2 Aims and objectives

The overall aim of this research is to investigate sediment delivery processes in upland catchments by incorporating estimates of contemporary inputs to reservoirs with long-term estimates of sediment yields from reservoir storage and by evaluating the linkages between catchment sources and reservoir sinks in a sediment budget framework.

To fulfil the aim of this thesis a series of objectives were developed:

1) To use a rapid assessment approach to identify potential sources and stores of sediment in the study catchments and apply an absolute dating technique to provide an historical assessment of sediment transfer.

2) To quantify contemporary suspended sediment yields and assess patterns of sediment transfer at different temporal scales to determine the output component of the catchment sediment system that forms an input to the reservoir sediment budget.

3) To quantify long-term sediment yields from sediments in reservoir storage using a combined approach incorporating core depth, sediment chronology (^{137}Cs), reservoir bathymetry and aerial photography.

4) To reconstruct the depositional sequence of sediments in reservoir storage and consider the extrinsic factors controlling sediment supply, transfer and deposition, evaluating the potential links within the sediment system.

Using this framework it may be possible to consider the potential effects of future climate change on sediment transfer in upland catchments.

1.3 Organization of the thesis

The thesis begins with a review of the concepts and relevant literature related to sediment delivery in the context of sediment budget research and covers methods of sediment yield estimation and dating techniques (Chapter 2). A detailed overview of existing research in upland catchments of the UK is included providing an overall context on which the thesis is based.

Chapter 3 includes a detailed discussion of the physical setting of the North Pennine region. The characteristics of the study catchments are outlined and justification given for site selection.

Chapter 4 describes the methodologies adopted, outlining the fieldwork sampling strategy and monitoring frameworks and laboratory procedures used.

Chapter 5, 6 and 7 present the results of this research. Chapter 5 provides a spatial framework for understanding sediment delivery in the study catchments by characterising the extent of contemporary sediment sources, defining the degree of slope/channel coupling and identifying the main zones of sediment storage. Discussion of the use of lichenometry as a technique for establishing a chronology of coarse sediment transport is included, providing an historical assessment of sediment transfer.

Chapter 6 focuses on contemporary suspended sediment dynamics and evaluates the sediment delivery system in relation to precipitation on a quasi-continuous and event based timescale. Sediment rating relationships are determined from monitored suspended sediment concentration and discharge data and patterns of sediment transfer during storm events examined to assess the linkages between supply and transfer of suspended sediment in these North Pennine study catchments.

Chapter 7 introduces the analysis of reservoir sedimentation in terms of estimating long-term sediment yields from sediment accumulation. The results of physical and radiometric analyses of core sediments provide preliminary information on the spatial and temporal distribution of sediment in the reservoir while variations in the down core particle size records are related to variations in historical rainfall patterns and subsequent fluctuations in reservoir water level.

Chapter 8 combines the results from Chapters 5, 6 and 7 that have evaluated the inputs, stores, outputs and linkages of the catchment sediment system to form a reservoir sediment budget. This chapter includes discussion of the main findings of this research in context to other published studies of sediment transfer in upland river systems in the UK.

Chapter 9 provides a concluding synthesis of the findings of sediment transfer in upland catchments. The original contribution made by this thesis is discussed and in conclusion, recommendations for further research are made.

CHAPTER 2 - FLUVIAL SEDIMENT DELIVERY AND REVIEW OF RESEARCH IN THE UK

2.1 Introduction

Information on erosion and sedimentation processes operating in drainage basins is an important requirement for the design and implementation of effective catchment management strategies (Walling, 1998). Traditionally emphasis was directed at quantifying sediment yields from drainage basins but as research has progressed the need to evaluate the major components of the sediment delivery system and the linkages between them has become apparent. Catchment sediment delivery systems are dynamic in space and time and the adoption of the sediment budget approach to evaluate the sources and stores of sediment and investigate the processes operating within fluvial systems has provided a greater understanding of the transfer of sediment in drainage basins.

This chapter begins with an overview of the concepts of sediment delivery in fluvial systems and addresses the use of sediment delivery ratios (SDR) and sediment budgets to account for the spatial and temporal variability in sediment transfer. Justification for sediment yield estimation is provided and the methodologies used to quantify sediment yields are discussed. An overview of the methodology and application of ^{137}Cs in evaluating catchment sediment delivery through dating of sediments is included. Sediment delivery in UK upland regions is then addressed and particular attention is directed to research in North Pennine catchments. Throughout this chapter reference is made to previous research providing context for the current study into sediment delivery in upland North Pennine catchments.

2.2 Sediment delivery in fluvial systems

Catchment sediment delivery is defined as the movement of sediment from on-site erosion in the catchment to the basin outlet (Walling, 1983). The sediment budget framework for assessing sediment delivery both spatially and temporally is now classed as a mainstream mode of investigation in sediment systems (Higgitt *et al.*, 2001; Warburton *et al.*, 2003). However, this framework has not always been adopted by researchers. This section reviews the issues related to the sediment delivery problem (Walling, 1983) and discusses some of the methods adopted to tackle it.

Sediment yield is the total sediment outflow from a catchment per unit of time and area, measured at a given cross section in a river or at a single point in a sediment sink (Jansson, 1988). Sediment yield is not always a direct indication of the degree of erosion in the drainage basin as it accounts only for the material that leaves the catchments at a single point in time. Eroded sediment is often deposited before it reaches the monitoring station, stream channel, reservoir or lake (Woodward and Foster, 1997). The fluvial sediment system is a cascade of sediment detachment, transfer and deposition with the outputs of each phase of the system forming the inputs to the next. An individual sediment particle within this cascade model of transfer may move through a number of storage phases before it reaches the exit of the drainage basin. Floodplains, channel bars and the base of hillslopes are all potential storage zones that generally increase in number with catchment size. The residence time of sediments in storage is dependent on the magnitude and frequency of discharge events, the characteristics of the sediment in storage and the location of the store in relation to the active channel. These spatial and temporal scales of variability in sediment delivery cannot be determined from catchment sediment yields at the basin outlet. Traditional methods employed to estimate sediment storage in river basins have included a comparison of upstream and downstream sediment loads to quantify floodplain deposits and the use of repeated channel cross-section surveying (Walling *et al.*, 2000).

The SDR defines the proportion of eroded sediment that leaves the drainage basin as part of the fluvial sediment load. Woodward and Foster (1997) note that the concept of the SDR is central to the understanding of catchment sediment storage. In order to define the SDR for a catchment it is necessary to obtain estimates of gross erosion in the catchment to compare to estimates of sediment yield from the basin outlet. Foster *et al.*, (1996) report a SDR of 27% for the catchment of Slapton Lower Ley in South Devon. Upstream erosion rates of 107 t km^{-2} yr^{-1} were estimated from the River Start catchment and annual sediment yields of 29 t km^{-2} yr^{-1} recorded at the basin outlet of Slapton Ley. The magnitude of the SDR for a particular catchment can be determined by a range of environmental and geomorphological factors that operate on a variety of spatial and temporal scales. These factors include the nature, extent and location of the sediment sources and stores, relief and slope characteristics, the drainage pattern and channel characteristics, vegetation cover, land-use and soil texture (Walling, 1983). The variability in these physical aspects of drainage basins is likely to result in variations in sediment erosion, storage and remobilisation in and between drainage systems. An example is the discontinuity in the temporal and spatial delivery of sediment during storm events. Sediment is mobilised from different sources providing different signatures for events of the same magnitude and frequency. Individual SDR can therefore be determined for each event but no assessment can be made regarding the nature of the sources and sinks activated during different events.

The SDR approach to quantifying sediment transfer does not account for the spatial and temporal complexity of catchment sediment delivery dynamics (Woodward and Foster, 1997). This issue relates to the problem of attempting to represent the sediment delivery characteristics of a catchment with a single number (Walling, 1983). Other attempts to address these problems of spatial and temporal complexity in sediment transfer and issues of sediment provenance from varying locations throughout the drainage basin have included modelling of sediment delivery processes at the basin scale using spatially distributed approaches (cf. Ferro and Minacapilli, 1995). This approach requires the choice of a soil erosion model, spatial disaggregation criterion of the sediment delivery process and also division of the basin into a series of morphological units (Ferro and Minacapilli, 1995). This is a complex technique that addresses the sediment sources in the sediment delivery problem but fails to account for the storage elements of the system. In recent decades researchers have used sediment budgets to identify the location of sediment sources and sinks and to quantify the active processes occurring within catchments (Dietrich and Dunne, 1978; Reid and Dunne, 1996). This sediment budget approach alleviates some of the uncertainty in evaluating sediment delivery dynamics inherent in the SDR approach.

2.3 The sediment budget approach

Sediment budgets provide a conceptual and quantitative model of sediment-transport magnitudes and pathways for a given time period (Rosati and Kraus, 1999) and have been developed for a variety of sites around the world (c.f Reid and Dunne, 1996, pg 125). A classic example is that of Coon Creek Basin in southwest Wisconsin by Trimble (1981) that highlights the importance of erosion and remobilization and also the variations in sediment delivery efficiencies in river basins. This investigation established two sediment budgets for the periods 1853-1938 and 1938-1975. Accelerated erosion during the first 85 years of study contributed 2080 t km^2 yr^{-1} of which 5% appeared at the output. This was a result of colluvial storage of sediment. The next 37 years recorded a decrease in erosion to 1640 t km^2 yr^{-1} due to improved land management practices, but an increase in sediment yield of 7% discharged at the mouth. Despite the accelerated erosion during the first study period, the buffering effect of the drainage system resulted in a smaller percentage output than that during the second period of study where sediment stores were mobilised. This highlights the variations in delivery within a drainage basin over time as a result of land use change.

A more recent example of application of the sediment budget approach is the study by Kern and Westrich (1997) on a reservoir catchment on the Neckar River, Germany. Using a series of field measurements of channel bathymetry it was found that sedimentation and erosion occurred primarily in the lower, backwater section of the reservoir. The total sediment loads transported from this zone during three storm events from 1993-1995, were used to calibrate a numerical model that was then employed to simulate sediment transport over a 45-year period. It was concluded that from 1950 to 1978 the reservoir had served as a sediment trap and since then as a temporary storage basin for sediment.

The work of Stott *et al.* (1986) is an example of the sediment budget approach applied to investigate the downstream impacts of afforestation and deforestation for two upland catchments in the Balquhidder basin, Scotland. The Monachyle Glen and Kirkton catchments were moorland and forested drainage basins respectively. The inputs of suspended sediment from the tributary streams and the outputs of sediment in both catchments were in approximate agreement but low delivery ratios for bedload sediments implied storage of tributary bedload in the main channel (Stott *et al.*, 1986). Bank erosion was identified as a potential sediment source in both catchments with landslides occurring at the end of the monitoring period in the moorland catchment (Stott *et al.*, 1986). The landslide had yet to contribute to the sediment yield at the basin outlet but identifying its location and noting its potential for contributing to future basin yield estimates is one of the benefits of adopting the sediment budget approach in investigating catchment sediment delivery. Further research into bank erosion processes operating in these forested and moorland catchments by Stott (1997) revealed that erosion rates were significantly lower on afforested streams than on nearby un-forested streams. This was related primarily to the incidence of frost occurrence that occurred half as frequently on forested stream banks than on moorland stream banks (Stott, 1997). The identification of stream banks as sediment sources using the sediment budget approach by Stott *et al.* (1986) prompted further research into the processes of sediment supply in the Monachyle Glen and Kirkton catchments. These sediment budget studies provide information on the efficiency of the sediment delivery system in terms of storage and remobilisation, which is one of the many advantages of the sediment budget approach.

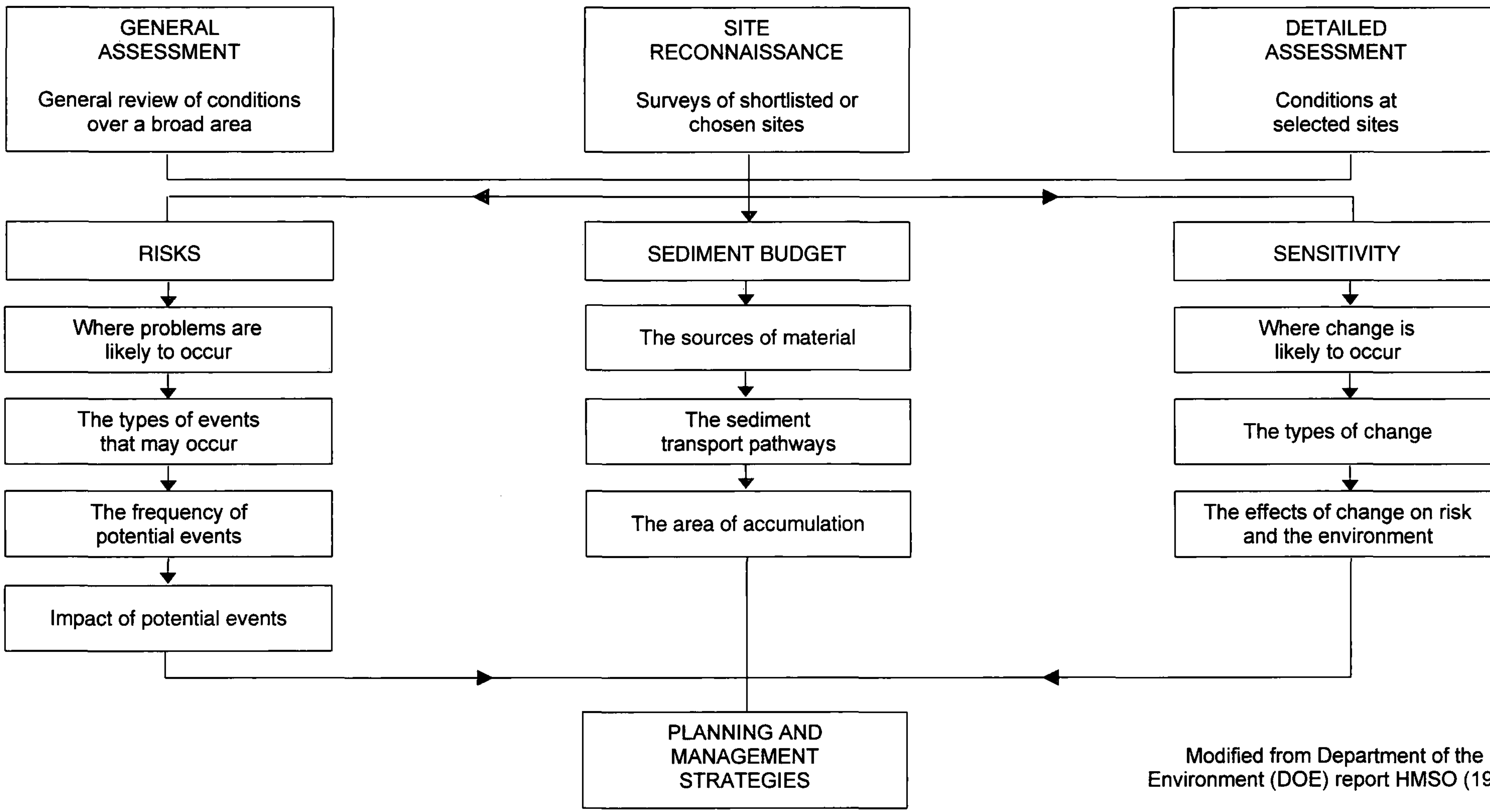
There are also a number of limitations inherent in the application of sediment budgets and despite the obvious utility of the approach it is often difficult to develop a comprehensive budget for a river system (Walling and Collins, 2000). This is attributed to the logistical problems relating to the various measurement techniques for each component of the sediment budget and the temporal and spatial variations in the processes that they measure (Dietrich *et al.*, 1982; Phillips, 1991). This has lead to the development of sediment budgets being restricted to smaller river basins (<100 km^2) or has focussed on particular components of the delivery system such as stream-channel coupling (Walling and Collins, 2000). However, it is more productive to have several strategically placed sediment budget assessments (Warburton *et al.*, 2003) than have large-scale investigations that do not account for temporal and spatial variations in sediment transfer.

In summary, the sediment budget approach identifies the structure of the sediment system by characterising sediment sources, transfer processes and linkages (Warburton *et al.*, 2003). This approach has been adopted by policy makers and resource managers in the UK to provide an understanding of the functioning of the sediment delivery system. Figure 2.1 shows the elements of earth science investigation required for sustainable planning and management of drainage basins specified by the Department of the Environment (DOE) (1995). This flow diagram highlights the key considerations relevant to the decision making process and can be applied from the catchment to the regional scale. What is clear from Figure 2.1 is the central role taken by sediment budget research in planning and management strategies. Despite this importance, few sediment budgets have been developed for upland catchments in the UK.

2.4 Sediment yield estimation - justification and methodologies

Traditionally, measurements of suspended sediment and discharge in rivers have been used to estimate sediment yields from drainage basins using sediment-rating curves (e.g. Walling and Webb, 1982; Labadz, 1988). These sediment yields have been used for assessing catchment disturbance due to afforestation (Johnson, 1988, 1993; Stott and Marks, 1998) and sediment-associated transport of nutrients and contaminants

Figure 2.1 The main elements of earth science investigations



Modified from Department of the Environment (DOE) report HMSO (1995)

(Macklin *et al.*, 1992a & b, 1997). Quantifying sediment and water flux at the outlet of a drainage basin is important for reservoir design as these are the determining factors controlling the mode of operation of a reservoir and hence the design of the spillway and outlet works of the dam (Mahmood, 1987). By assessing erosion and sedimentation rates within a drainage basin and relating these to sediment yield, it is possible to estimate the efficiency of the sediment delivery system and the sensitivity of a river basin to environmental change or catchment management (Walling *et al.*, 2000).

Despite the advantages of sediment yield estimation for management of upland catchments there are few data available in Britain. This is in part due to the expense incurred in establishing and maintaining sediment-monitoring stations. The variable methodologies employed in estimation of sediment yields together with the variable length of records create problems in comparison between yield estimations from different upland areas and at different spatial scales. Drainage basin sediment yields fluctuate in response to annual variations in runoff (Walling, 1978; Foster, 1995). Most high frequency monitoring in the UK is conducted over short timescales that are unsuitable for determining annual variations from single point measurements. Foster (1995) comments on the lack of long-term monitoring which restricts the identification of trends in sediment yields in response to changes in climate or land management practises. He discusses the use of reservoir and recent lake sediments as alternative sources of proxy data overcoming the spatial and temporal shortcomings of river monitoring. Dearing and Foster (1993) considered three methods of obtaining sediment yield and erosional data from reservoir sediments:

1. Comparing survey data of reservoir bottom sediments, calculating average sediment volumes between known survey dates.

2. Individual core sampling, dating and analysis to calculate accumulation rates, complimented with proxy erosion data, mineral magnetics, palaeoentological, or chemical data where available.

3. Core correlation related to a master dated sequence accounting for spatial variations in accumulation rates and through averaging or three-dimensional mapping of the accumulation rates to calculate total sediment yields.

Reconstruction of changing accumulation rates through time provides an opportunity to examine the effects of historical climate and land-use changes on sediment yields from drainage basins, provided corrections are made for trap efficiency of the water body

(Foster and Lees, 1999a & b). Repeated data surveys of reservoir sedimentation can provide an adequate representation of sediment volumes over long or short timescales depending on the frequency of surveying. Advantages of using the reservoir surveys for calculating sediment yields include the relative simplicity of data collection (Butcher *et al.*, 1992) and the ease of yield calculation without the use of generalised statistical models of sediment erosion and transport or spatial extrapolation of point measurements (Stott *et al.*, 1988). For example, sediment yield estimations using reservoir survey data have been used to calculate sediment yields in studies based in Scotland (Duck & McManus, 1987, 1990, 1994), the Peak District (Hutchinson, 1995) and the Southern Pennine region (Stott, 1985, 1987; Butcher *et al.*, 1993; Labadz *et al.*, 1991, 1995; White *et al.*, 1996b). Duck & McManus (1987) studied the bottom sediments of nine reservoirs in the Midland Valley of Scotland. Using isopachyte maps constructed from thickness variations of sediment deposits, sedimentation and catchment sediment yields were established. Six of the nine catchments were dominated by moorland with local afforestation, the remainder supported agriculture and woodland. These catchments range from 1.53 to 23.5 km^2 in area, with sediment yields ranging from 2.1 t km^{-2} yr^{-1} to 52.0 t km^{-2} yr^{-1} (Duck & McManus, 1987). The study showed the nature of land use to be a major contributing factor in determining annual sediment yields. The catchments dominated by afforestation had yields of greater than 10 t km^{-2} yr^{-1}, moorland catchments ranged from 4 – 41 t km^{-2} yr^{-1} and agriculturally-dominated catchments from 31 - 52 t km^{-2} yr^{-1} (Duck & McManus, 1987). The use of sedimentation surveys in upland regions is documented in the work of Butcher *et al.* (1993). Reservoir sedimentation rates were calculated from sedimentation surveys from 28 selected reservoirs in the Southern Pennines (Butcher *et al.*, 1993). The measurements of reservoir capacity losses since construction showed spatial variation in the rate of infilling, with sediment yields ranging from zero to 1074.6 t km^{-2} yr^{-1} (Butcher *et al.*, 1993). These yields are considerably higher than the typical yields suggested for small upland catchments, ranging from 30 t km^{-2} yr^{-1} (Walling & Webb, 1981b) to 50 t km^{-2} yr^{-1} (Newson, 1986).

These surveys are useful in providing low-resolution sediment yield estimates but do not provide information on the physical nature of the sediments for determining source areas from catchment erosion. The individual and multiple core correlation approaches using physical and radiometric methods of determining sediment chronologies produce a more detailed reconstruction of sedimentation in lakes and reservoirs (Dearing & Foster, 1993) with regards to temporal and spatial catchment erosion.

There have been several studies comparing sediment yields determined from single cores with data using the core correlation approach. When only one core is used in determining sediment yields from reservoirs, there is no account for any spatial variability associated with sampling position (Foster & Charlesworth, 1994) and the point of average sediment accumulation on the reservoir bed may vary over time (Dearing, 1986). To investigate this concept, Dearing (1992) studied sediment cores from Llyn Geirionydd in North Wales. Accumulation estimates using a single dated core were compared to the mean accumulation rates from a suite of 32 cores taken from the same site (Dearing & Foster, 1993). Both data sources are valuable, the single dated core giving a more detailed record of relative trends in sediment flux from the catchment and the core correlation approach producing more accurate total sediment flux values (Dearing & Foster, 1993). Variability in accumulation rates was found to be greater between cores than within the main master core. This suggested that the effects of mining, forestry and farming in the catchment over the last 100 years had a greater effect on the pattern of sedimentation to the lake than on total sediment loads (Dearing & Foster, 1993). In this case study, the use of single dated cores appears to have provided relatively accurate data on catchment responses, with 19 zones showing erosional detail through time at a greater resolution than the correlated cores where time zones were reduced to four (Dearing & Foster, 1993).

An alternative strategy for determining sediment yields using core correlation techniques based on core location was developed by Evans (1997) and further discussed by Evans and Church (2000). The technique involved dividing the area of a series of study lakes in British Columbia into a number of Thiessen polygons and the core at the centre of each polygon was representative of the entire area. This method proved useful in reducing the error associated with spatial variability of sediment accumulation that is commonly linked to variations in morphology of the basin and in the proximity of dominant sedimentary inputs.

Studies comparing contemporary stream loads to sediment yield estimates from lake accumulation records have produced interesting results. Foster *et al.* (1985) used the combined approach of stream monitoring and lake-based sedimentary analysis to determine sediment yields in the Merevale catchment, North Warwickshire, UK. Separate sediment yield estimates from lake-based sedimentary analysis were made for four different time zones ranging from 1861 to 1982. Crude estimates of inputs from lake shoreline erosion and atmospheric fallout were accounted for in the final estimates that ranged between 47.1 and 142.3 kg ha^{-1} yr^{-1}. Annual suspended sediment yields recorded at the lake inflow for the period January 1982 to January 1983 was 64.8 kg ha^{-1} yr^{-1}. Overall comparison of the annual sediment yields from the two methods showed comparable but low (50-200 kg ha^{-1} yr^{-1}) levels of sediment loss from the catchment (Foster *et al.*, 1985). Foster and Lees (1999b) noted that caution must be taken when comparing lake-based sediment yields with those determined from stream monitoring. Yields accumulated in lakes include those inputs from lake shoreline erosion, atmospheric fallout and exclude those sediments lost from the reservoir via the outflow and are therefore not directly comparable to yields from stream monitoring. Annual yields based on direct stream monitoring are yields from a single years observation and yield determined from lake accumulation are averages calculated from decades of accumulation. Despite these discrepancies associated with direct comparison of sediment yields using two different methods, quantifying sediment yields using different methodologies forms the basis of the sediment budget approach where the yield estimates are components of more complex catchment sediment system.

2.5 Trap efficiency of reservoirs

Trap efficiency is defined as the weight of sediment that is retained in a reservoir in any one year expressed as a ratio of the total weight of sediment inflow in that year (Gill, 1979). Calculating the trap efficiency of a water body is essential when estimating sediment yields from sediments in storage and is an important consideration when developing a reservoir sediment budget. Brown (1944) carried out a pioneering study of reservoir sedimentation and plotted trap efficiency against catchment area. The calculation of trap efficiency in this study was oversimplified as it only accounted for the capacity of the reservoir and the catchment area and did not include any other parameters.

The trap efficiency curves created by Brune (1953) were based on observations and surveys of 44 American reservoirs and calculated from the ratio between reservoir capacity to average annual inflow for different sediment sizes. This method was widely used and considered more accurate than the curves of Brown (1944) as annual inflow was included in the model. The revised curves of Brune (1953) are still considered to provide a rough estimate of reservoir trap efficiency as they fail to account for reservoir flow dynamics and no adjustments are made for overflow sediment from upstream reservoirs (Borland, 1971).

Heinemann (1981, 1984) revised the curves of Brune (1953) and determined trap efficiency by having accurate flow measurements and sampling from both the inflow and outflow of the reservoir but this approach still does not account for reservoir flow dynamics. Churchill (1948) produced a more comprehensive model that considered reservoir flow dynamics and overflow sediment from upstream reservoirs (Trimble & Bube, 1990). The model takes into account both detention time and velocity of flow through the reservoir and expresses a 'sedimentation index' which represent the period of retention time divided by mean velocity (Brune, 1953). The trap efficiency curves in Churchill's model were calculated from direct sediment transport measurements over periods of three to nine months (Trimble & Bube, 1990). Borland (1971) introduced additional sediment transport data measurements and the data of Churchill (1948) and Borland (1971) were used by Trimble and Bube (1986) to revise the original curves of Churchill (1948). These revised trap efficiency curves could be used to calculate sediment through a cascading reservoir system and are satisfactory when the data are available. Unfortunately, the information required for this model is not readily available for most reservoirs (Brune, 1953).

The sediment budget approach offers an additional method of determining reservoir trap efficiencies in water bodies. Quantification of input, storage and output components of sediment budgets enables calculations of trap efficiency based on the sediment balance equation. There are few examples of comprehensive sediment budget studies for reservoirs, where sufficient data are collected to estimate trap efficiency using this method.

2.6 Core correlation and dating

Sedimentation rates vary spatially across lake or reservoir beds as a result of sediment focussing, variations in sediment influx to water bodies and reworking of sediment by re-suspension. Reconstructing sediment yields from bottom sediments involves the identification of time synchronous layers within the sediments in order to calculate sediment volumes (Foster *et al.*, 1990). The spatial distribution of sediment cores is important when addressing these variations in sediment deposition and methods of core correlation and dating are required to deal with this problem. Dearing (1986) reviewed the techniques of core correlation and stated that there should be both 'areal continuity' and 'areal synchroneity' in sediments used for correlation. The sediment used should be deposited in similar proportions over the bed surface and should be either persistent and immobile, or transient in respect to its form or position at a relatively constant rate over the bed surface (Dearing, 1986). Table 2.1 lists methods of core correlation discussed by Dearing (1986) and Foster *et al.* (1990).

Table 2.1 Core correlation techniques.

Correlation techniques	Characteristics used	Examples of past studies
Visible stratigraphy	Annually laminated sediment Changes in texture and colour Tephra layers	Simola *et al.* (1981) Dearing (1979, 1983) Turney *et al.* (1997); Mackie *et al.* (2002)
Palaeoecological stratigraphy	Pollen horizons Diatom assemblages	Edwards and Rowntree (1980) van der Post *et al.* (1997)
Chemical statigraphies	Loss on Ignition	Evans (1997)
Radioisotope records	^{137}Cs in surface sediments	Walling and He (1992); Ritchie and McHenry (1990)
Magnetic correlations	Based on remanent and induced magnetic properties	Walden *et al.* (1997); Thompson and Oldfield (1975)

(Modified from Foster *et al.* (1990))

Visible stratigraphic markers can be either regular, as in annually varved sediments or irregular marking sporadic influxes of allochthonous or autochthonous sediments due to variations in geomorphic activity in the catchment (high magnitude, low frequency event) or internal conditions in the water body (changing water levels). These irregular layers can vary by colour and or textural changes and can be classified using the Troels-Smith (1955) method of stratigraphic identification. Irregular layers of coarser sediments potentially indicate variations in stream power or activation of alternative source areas in catchments (cf. Curr, 1984, 1995) but care must be taken as coarse-textured layers in littoral areas may be the result of local distribution of sediment that may not be synchronous with bands in cores taken from the centre of the lake bed (Dearing, 1986). Tephra layers can provide ideal markers for correlation as they are easily visible and distinguishable from sedimentary layers. Tephra is also used for determining core chronologies as they provide age-equivalent horizons of known volcanic eruptions.

The remaining correlation techniques in Table 2.1 are reliant on physical and or chemical processing for analysis. Diatom analysis, loss on ignition (LOI) and mineral magnetism can be used to reconstruct environmental conditions under which the sediments were deposited but can not be used directly for establishing core chronologies. Studies often incorporate a number of these correlation techniques to distinguish sediment layers and then choose a relevant method of dating which is dependant on the timescales of study. The suite of methods available for dating sediments from the Quaternary period are discussed in Lowe and Walker (1997, pg. 238). For reservoirs constructed over the last 200 years or less, a combination of caesium-137 (^{137}Cs) and lead-210 (^{210}Pb) analyses have been most commonly used in providing age estimates of ±10 years or less (Foster *et al.*, 1990).

2.6.1 Sources of ^{137}Cs in the environment

The artificial radionuclide ^{137}Cs has a half life of 30.2 years and is present in the environment as a result of nuclear weapons testing that began in 1954 and ended on 26th April 1980 when the last scheduled explosion was carried out at the Lop Nor test site in China (Cambray *et al.*, 1987; Higgitt, 1991). Weapons testing resulted in a global, non-uniform distribution of ^{137}Cs with the greatest levels recorded in the Northern Hemisphere and peaks in the mid-latitudes (Davies and Shaw, 1993). The concentrations of ^{137}Cs in the atmosphere have varied over time, which in turn reflects the frequency of bomb testing. The ^{137}Cs fallout record shows a small peak in 1959 and a higher peak in 1963, which correspond to the increased incidence of atmospheric nuclear weapons testing during those periods (He *et al.*, 1996).

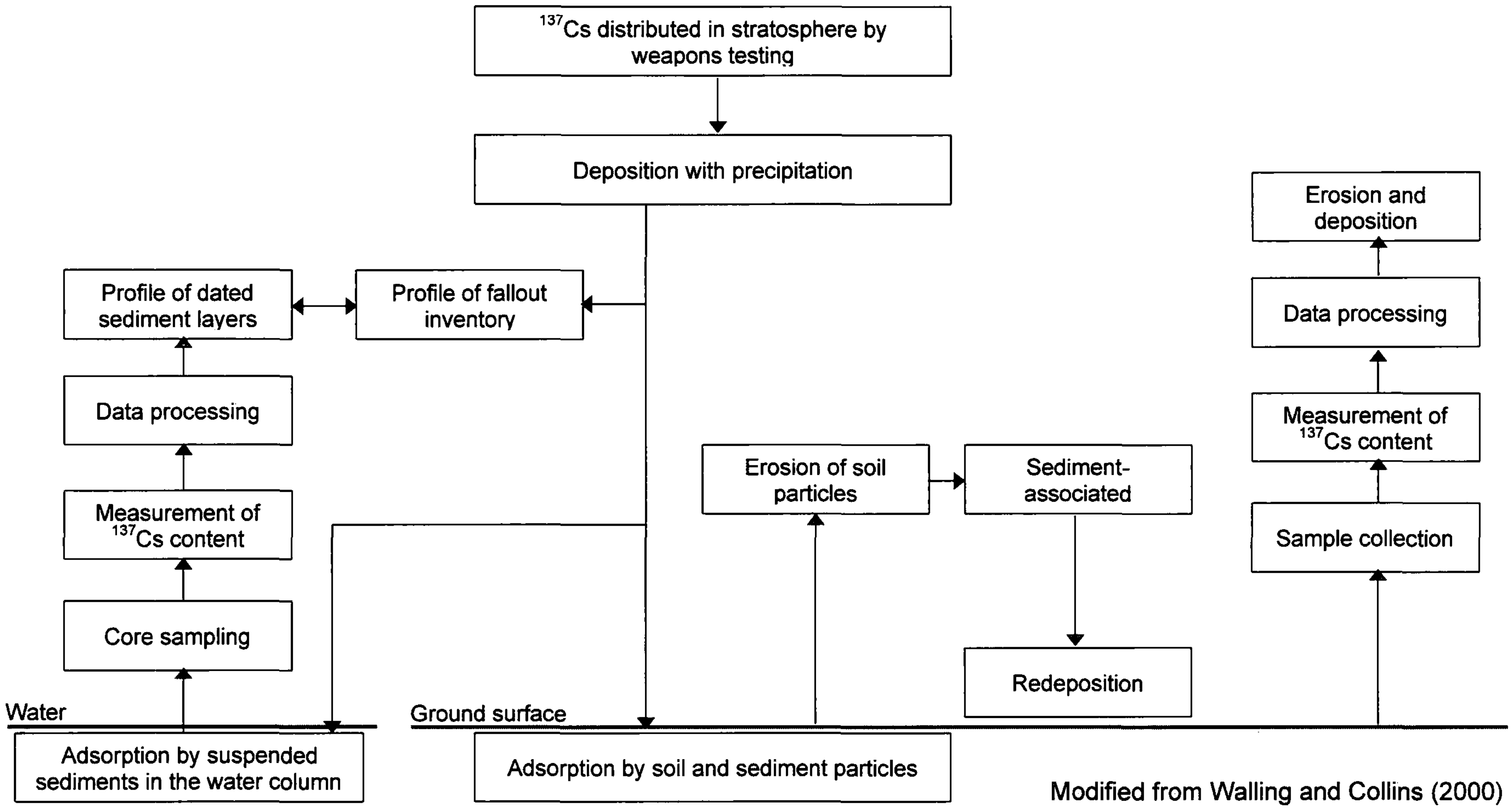
A secondary source of ^{137}Cs to the atmosphere was from the release of a radiation cloud from the Chernobyl nuclear power plant accident in 1986. Radionuclides were unevenly deposited across the Northern Hemisphere between May 2nd and May 4th 1986 (Smith & Clark, 1986) resulting in an increase of 5% in the global and 40% in the UK inventory of ^{137}Cs (Cambray *et al.*, 1987). The Chernobyl radiation plume did not reach the stratosphere and therefore there is marked spatial variability in fallout of Chernobyl ^{137}Cs (Walling and Collins, 2000). At the regional scale fallout data indicates that there is a close relationship between ^{137}Cs concentration and precipitation and despite the lack of empirical data on the spatial variability of fallout the general assumption is that there is uniform fallout of ^{137}Cs at the local scale (Walling and Collins, 2000).

2.6.2 Adsorption of ^{137}Cs by soils and sediments

Figure 2.2 is a flow diagram showing the transmission of ^{137}Cs from the atmosphere to the earth's surface and provides the basis of the ^{137}Cs approach to determining catchment sediment erosion and deposition. When deposition occurs on the surface of a water body, ^{137}Cs adheres to suspended sediment particles that settle out and accumulate as bottom sediments (He *et al.*, 1996). The fallout of ^{137}Cs on the ground surface is rapidly and strongly adsorbed to soil and sediment particles with the result that subsequent redistribution of ^{137}Cs reflects the movement of these particles (Walling and Collins, 2000). Investigations into the rapid and effective adsorption of ^{137}Cs to soil and sediment particles by He and Walling (1996) and Livens and Baxter (1988) provides evidence that supports the assumption that vertical and lateral redistribution of ^{137}Cs enriched sediment is due to erosion, transport and deposition of soil and sediment particles.

Dating sediments in lakes and reservoirs using the ^{137}Cs approach has been based on the assumption that variations in the concentration of ^{137}Cs in deposited sediments will be similar to that of atmospheric fallout at the water surface. This indicates that the peaks in concentration in deposited sediment will be synonymous with the 1963 peak in fallout and the deepest sediment containing measurable ^{137}Cs will have been deposited in 1954 (He *et al.*, 1996), provided that diffusion is negligible.

Figure 2.2 The basis of the ^{137}Cs approach for dating sediments and estimating rates of erosion and deposition



Modified from Walling and Collins (2000)

2.6.3 Application of the ^{137}Cs approach to assessing sediment erosion and deposition

Ritchie and Ritchie (2000) provide a bibliography consisting of (120 pages) references to ^{137}Cs based research related to erosion and sediment deposition worldwide. Fallout radionuclides of ^{137}Cs have been used for the last three decades to date reservoir and lake sediments in upland catchments of the UK (cf. Pennington *et al.*, 1973, 1976; Eakins *et al.*, 1981, Foster, 1995; Bonnet and Appleby, 1991; Bonnet and Cambray, 1991; Rowan *et al.*, 1993; Walling, 1994; Hutchinson, 1995; van der Post *et al.*, 1997; Foster and Foster and Lees, 1999b; Haworth *et al.*, 2000). Some of these studies have reported trends in down-core ^{137}Cs that conform to the classic trend relating to atmospheric fallout in the Northern Hemisphere (cf. Pennington *et al.*, 1973, 1976; Bonnet and Appleby, 1991; Foster and Lees, 1999b) while others show little or no similarity to the classic fallout shape (van der Post *et al.*, 1997; Haworth *et al.*, 2000). Deviations from the atmospheric fallout record have been attributed to post-depositional mobilisation of ^{137}Cs and downward migration of Chernobyl ^{137}Cs (cf. Howarth *et al.*, 2000) and to substantial sediment-associated ^{137}Cs input from the catchment (van der Post *et al.*, 1997). One of the most important problems related to dating sediments using ^{137}Cs is the potential unreliability of the record. Processes of bioturbation, mixing, downward molecular diffusion and adsorption of this radionuclide can lead to errors in dating of sedimentary horizons (Foster *et al.*, 1990).

A number of studies have used the peaks in the ^{137}Cs record to identify periods of increased sedimentation that have in turn been related to major changes in land use (Ritchie & McHenry, 1990; Dearing, 1992; Walling & Woodward, 1992; He and Walling, 1996, van de Post *et al.*, 1997). Dating of sediment cores taken from Blelham Tarn in the Lake District revealed accelerated erosion in the recent sedimentary record (van der Post *et al.*, 1997). Measurements of ^{137}Cs in recent sediments provided a clear reference dating point for post-1950 sedimentation. There was overwhelming evidence for accelerated sedimentation from the late 1980s and these sediments were determined as being predominantly allochthonous in origin. Values of ^{137}Cs concentration and magnetic signatures of the sediments were used to confirm that catchment soils were the dominant source of recent allochthonous sediments and the onset of the accelerated erosion was linked to increases in sheep stocking densities in the catchment.

In addition to ^{137}Cs being a valuable dating tool for recent sediments, the research carried out in Blelham Tarn suggests that ^{137}Cs is also a valuable tool for estimating surface soil erosion and deposition on the ground surface. The methodology involves establishing a reference inventory at an undisturbed location in a catchment that has experienced no erosion or deposition and comparing it to the ^{137}Cs inventory of sediments from selected disturbed sites in the catchment. Any variations between the inventories can be estimated using models based on relationships between ^{137}Cs loss or gain and soil erosion or deposition (Walling and Collins, 2000). The concentration of ^{137}Cs in the source material at these disturbed sites can be used as a fingerprint when assessing zones of erosion and deposition in drainage basins. Walling & Bradley (1990) suggest that the ^{137}Cs concentration of source material and suspended sediment affords an excellent fingerprint in determining the relative importance of the major sediment sources in a drainage basin. In the UK the majority of research using ^{137}Cs as a sediment fingerprint has been carried out in lowland agricultural areas, comparing sources from cultivated and uncultivated soils (He & Walling, 1997).

Little work has been carried out on the use of ^{137}Cs in identifying erosion in peaty upland soils and upland reservoir sedimentation. However, research has been conducted on catchment scale deposition and re-distribution of Chernobyl-derived ^{137}Cs and ^{134}Cs in upland North Wales (Bonnett *et al.*, 1989; Higgitt *et al.*, 1993) and Ireland (Colgan *et al.*, 1993). The applications of ^{137}Cs measurement in geomorphological research are limited to areas where the rates of erosion are sufficiently high to distinguish ^{137}Cs depletion from baseline variability (Higgitt, 1990). Concentrations of ^{137}Cs are highest in surface sediments and often not detectable in sediments from actively eroding channel margins where processes of undercutting are prevalent. As a result of the spatial variability of atmospheric fallout of ^{137}Cs in upland areas and the dominance of channel erosion over surface erosion, the use of ^{137}Cs as a fingerprinting tool to quantify erosion in upland areas is limited. Results reported by Higgitt *et al.* (1993) on the Lake Vyrnwy catchment in Wales highlight these problems of spatial variability of Chernobyl-derived ^{137}Cs deposition limiting its use in the assessment of erosion rates in upland systems.

Walling (1998) discusses the opportunities for using ^{137}Cs in the study of watershed sediment budgets. Estimates of rates and patterns of soil erosion, identification of sediment sources and estimation of rates and patterns of overbank sedimentation on floodplains can all be determined through the use of ^{137}Cs. As mentioned previously, the majority of sediment budgets constructed using ^{137}Cs in the UK have been developed in lowland catchments. Examples include assessing the role of channel and floodplain storage in the River Ouse, Yorkshire (Walling *et al.*, 1998, 1999) and quantifying suspended sediment fluxes in the Humber catchment (Wass *et al.*, 1999).

Again due to the dominance of channel erosion in headwater catchments the use of ^{137}Cs as a fingerprint in upland sediment budgets is limited.

In summary, the use of ^{137}Cs analysis in sediment delivery research provides a non-destructive method of dating reservoir core sediments and previous research has proved the approach provides a valuable dating tool for recent sediments. However, the ^{137}Cs approach does not provide sedimentation estimates for discrete hydrological events or short-term time periods (Walling & Collins, 2000). Furthermore, although the fallout from weapons testing was distributed globally, there is still spatial variation in the concentrations deposited that are dependant on precipitation patterns. This can limit the use of the ^{137}Cs technique when concentrations become too low and the counting times of radionuclide levels in sediment samples are increased dramatically. This could be problematic when comparing erosion and sedimentation rates between different case study sites.

2.7 Sediment delivery in UK upland regions

In a discussion of global patterns of sediment yield, Jansson (1988) concludes with a call for intensive studies in small river basins with well-defined environmental conditions to be able to evaluate variability within and between larger basins. Although the importance of monitoring suspended sediment loads in rivers has been clearly recognised, there has been no attempt to establish a national monitoring programme in Britain (Walling, 1990). At the regional scale however a number of strategic studies of catchment sediment yield estimation in upland regions of the UK have formed the basis of further research.

Experimental catchment monitoring programmes at Plynlimon in Mid Wales, Balquidder in Scotland and Moor House in the North Pennines are examples of long running monitoring programmes in the UK. Investigation into sediment delivery in each of these areas has played an important role in understanding catchment response to environmental change in upland regions. Research into fluvial sediment systems in other areas of the UK has tended to be limited in duration to the periods of Ph.D research. These studies have tended to concentrate on the effectiveness of short-lived events such as storms and floods (Egglestone, 1881; Crisp, 1966; Crisp and Robson, 1979; Newson, 1980a; Werritty, 1984; Carling, 1983, 1986a & b, 1987a & b) and the influence of land use change on sediment supply in terms of forestry (Stott, 1986, 1997, 1999) and mining (Macklin and Lewin, 1989). In an attempt to gain a greater understanding of the catchment processes involved in the sediment transfer, studies have concentrated on the connectivity between certain system components e.g. coupling of hillslope to channel (Harvey, 1991) and stream bank to channel (Lawler, 1993; Stott, 1997, 1999; Stott and Marks, 1998). These studies have provided valuable information on process response to climate and land use change and have often formed part of a sediment budget.

The Institute of Hydrology initiated research in upland catchments in Plynlimon, mid-Wales in 1968, based on the collection of a wide range of geomorphological and hydrological data ranging from climatic averages to sediment yields. This was a paired catchment study that first compared the hydrological effects of different land uses (forest and grassland) and then progressed to monitor sediment transfer in the Wye and Severn catchments as environmental issues on sediment transfer came to the fore in the mid1970s (Kirby *et al.*, 1991). The effects of afforestation on erosion processes and sediment yields in the Plynlimon catchments were first described by Painter *et al.* (1974). This study concentrated on bedload movement in the Cyff and Tanllwyth catchments. The highest yields were recorded in the Tanllwyth catchment and these were attributed to the network of hand-dug herring-bone pre-afforestation drainage ditches (Kirby *et al.*, 1991). Little consideration was given to fluvial transport of sediment in suspension in the Plynlimon catchment until a large-scale regional study of the fluvial geomorphology of mid-Wales adopting the whole catchment scale approach was commissioned in 1979 (Kirby *et al.*, 1991). Leeks (1983, 1990) investigated the impact of the preparations for and impacts of clear felling on suspended sediment yields in the Hore catchment. There was an immediate rise in sediment yields at the beginning of the felling phase. The rating curves for the first year of the felling period indicated moderate to high yields, an order of magnitude greater than previous levels (Leeks, 1990; Kirby *et al.*, 1991).

The Plynlimon experiment was the first of two research programmes set up by the Institute of Hydrology investigating the effects of land-use change on runoff and water quality. The second programme was developed in the Balquidder catchments in Scotland in 1982 where a paired catchment experiment comparing runoff and sediment transfer in the moorland catchment of Monachyle and forested catchment of Kirkton was initiated. Stott *et al.* (1986) provides estimates of bedload and suspended sediment yields before the Monachyle catchment was ploughed and partly afforested and the Kirkton basin partly felled in 1986. A sediment budget approach was adopted in this study and as previously discussed (section 2.3) it provided information on catchment sediment sources (bank erosion, landslides) and sinks.

Research into sediment delivery in the Tees catchment was first carried out by Butcher *et al.* (1937). Winter (1950) discussed issues of siltation of impoundment reservoirs while Conway and Millar (1960), Crisp *et al.* (1964), Crisp (1966) and Crisp and Robson (1979) considered hydrology and sediment production and transfer at Moor House National Nature Reserve (NNR) in upper Teesdale. Crisp (1966) and Crisp and Robson (1979) studied the effects of discharge on the transport of peat in Rough Sike in upper Teesdale. These studies provided valuable information on the timing of peat transfer in Pennine streams. Results showed that 80% of annual peat loads were transported during storm events of over 5.6 times the annual mean discharge (Crisp and Robson, 1979). These discharge events occurred less than 3% of the time in the study year. Peaks in peat transport were recorded before peaks in storm discharge indicative of dilution effects of sediment supply. Crisp (1966) estimated peat erosion for the Rough Sike catchment at less than 1 cm yr^{-1} on actively eroding peat areas. These figures were based on peat yields at the basin outlet and did not account for peat in storage in the system.

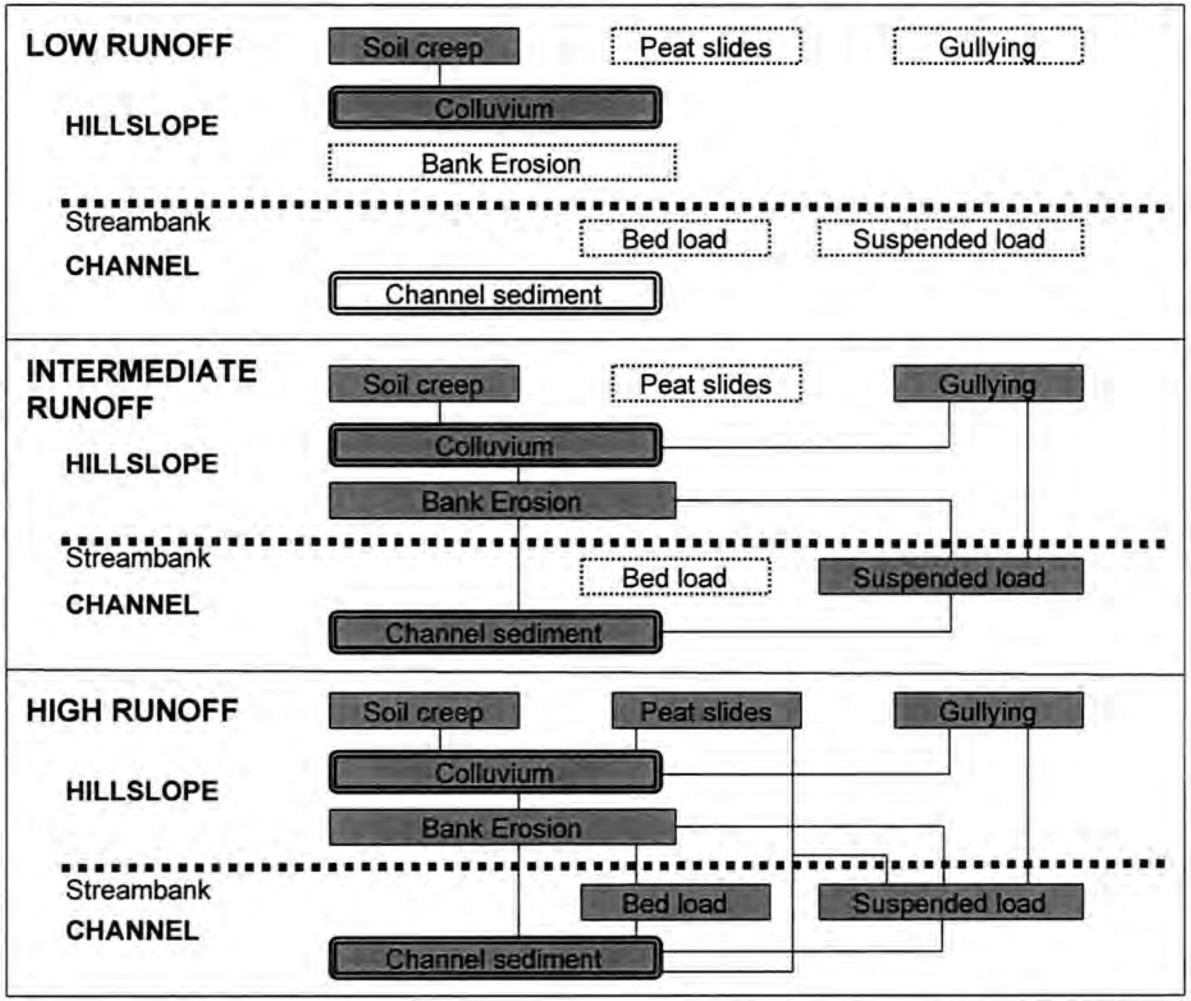
Imeson (1974) investigated the sources of sediment within a moorland catchment at Hodge Beck in the North Yorkshire Moors in relation to vegetation coverage. Catchment sediment delivery ratios of 40% indicated that less than half of the sediment eroded in the catchment made it to the basin outlet over the monitoring period. This was one of the first investigations of its kind into sediment sources in upland UK catchments and highlighted the importance of sediment storage. Carling (1983) conducted further research into the dynamics of suspended production and transfer in the catchments of Carl Beck and Great Egglestone Beck in the North Pennines. Mean suspended sediment concentrations measured during storm events on Carl Beck and Great Eggleshope Beck were 30 mg l^{-1} and 22 mg l^{-1} respectively but variability in the timing of sediment concentration peaks in relation to discharge peaks was recorded and progressive sediment exhaustion reflected variable sediment supply. Annual suspended sediment yields were not estimated for these North Pennine tributary streams, the emphasis of the research by Carling (1983) centred on the dynamics of suspended sediment loads during storm events.

Burt and Gardiner (1984) compared runoff and sediment production in eroded and un-eroded blanket peat sub-catchments of Shiny Brook in the Southern Pennines. Detailed storm hydrograph analysis confirmed that storm rainfall rather than antecedent conditions controlled storm runoff and sediment supply in the eroded sub-catchment appeared abundant unlike supply at the un-eroded site that was easily exhausted. This investigation concentrated mainly on the inputs and outputs of runoff and erosional systems and no annual estimates of sediment yields were made (Burt *et al.*, 1990).

Labadz (1988) contributed to research on hydrology and sediment transfer in blanket peat catchments by calculating annual sediment yields from a number of Southern Pennine catchments using a combined approach of reservoir sediments and stream suspended sediment monitoring. Long-term average organic sediment yields from Wessenden Head Reservoir together with volume estimates of peat erosion in the Shiny Brook catchment were used to estimate dates of the onset of peat erosion to AD 1800, that despite being crude (Burt *et al.*, 1990) were comparable to those of Tallis (1964, 1985). Labadz (1988) also investigated the sources of peat sediments and concluded that overland flow and collapsed gully systems were the major sources but indicated that erosion was by no means uniform in time or space. Source area identification was greatly complicated in the lower reaches of the channel as erosion of till deposits and bedrock added a mineral fraction to the suspended sediment load (Burt *et al.*, 1990).

Contemporary findings on erosion of blanket peat at Moor House NNR in upper Teesdale by Burt *et al.* (1998a) involved the resurrection of the gauging site located on Rough Sike by Crisp (1966). This was part of a study looking at long-term patterns of sediment yield from peatland catchments. The spatial and temporal patterns of sediment production and transport were investigated and initial observations of linkages between sources (banks, gully wash and alluvial fan deposits) and the channel made. A conceptual model of the sediment system in peat catchments at Moor House was developed as a framework for future quantification of in-catchment processes, and the connection between sources transport and storage under different hydrological regimes identified. Figure 2.3 is the schematic diagram of sediment delivery that has been modified to account for the main transport processes and storage elements recognised in the North Pennines. The model considers connectivity between sediment sources and sinks with the channel system under varying runoff conditions. During low flow sediment transfer is negligible, under high flow conditions connectivity between hillslope and channel results in activation of sediment transfer. This investigation was the first to assess the contemporary sediment budget and hydrological responses in a North Pennine catchment and forms the basis for future work quantifying contemporary sediment budgets in North Pennine catchments.

Figure 2.3 Conceptual model of the sediment system ofpeatland catchments under varying runoff conditions



(Modified from Warburton, 1998)

2.8 Overview of research into sediment delivery in North Pennine catchments

A summary of research undertaken within the North Pennine region related to catchment sediment delivery is given in Table 2.2, and examples of rates of processes from individual studies are included in Table 2.3. These tables highlight the scope of research into sediment budget components undertaken so far and form a basis on which sediment delivery response to contemporary and historical climatic conditions and land use change can be assessed. It is evident that most of the research has concentrated on the individual components of the sediment delivery system and the simple linkages between them. The majority of this has been carried out in Upper Teesdale at the Environmental Change Network (ECN) site of Moor House. These studies come in response to previous requests for a greater understanding of process and interaction of geomorphic systems, as more is known about the processes involved and the factors operating in geomorphic systems, the range of uncertainty will decrease (Leopold and Langbein, 1963). These studies provide valuable information into the behaviour of upland systems on a plot, reach and catchment scale.

As outlined in section 2.7 there have been numerous studies of sediment transfer dynamics in upland regions on event timescales (Labadz, 1988; Labadz *et al.*, 1991) and a number of studies have concentrated on linkages between certain components of the sediment budget (Harvey, 1994, 2001, 2002). The work of Carling, (1983); Crisp (1966); Crisp and Robson, (1979); Evans and Burt, (1998) and Burt *et al.* (1998a) contributes to the understanding of suspended sediment delivery in North Pennine upland catchments, while recent research carried out within the Wear catchment has concentrated on channel response to flooding and mining (Carling, 1986a & b, 1987a & b; Gifford, 2000; Warburton and Danks, 1998; Warburton *et al.,* in press) and the mechanisms and effects of peat mass movements (Warburton and Higgitt, 1998; Mills, 2002). There is a need to use the information obtained on the nature, activity and effectiveness of geomorphic processes operating from these component studies in order to develop and quantify sediment delivery using a sediment budget framework for North Pennine catchments.

2.9 Chapter summary

This chapter has provided an overview of the concepts of catchment sediment delivery that provides context for the current research. From evaluation of the literature the

Table 2.2 Overview of research carried out on catchment sediment systems in the North Pennine region.

Research field	Component studied	Location of research	Source
Coupling of organic sources to the stream system	Peat block transport	River Tees and Trout Beck, upper Teesdale	Warburton and Evans (1998); Evans and Warburton (2001)
	Peat mass movements	Hart Hope, upper Teesdale	Warburton and Higgitt (1998); Mills (2002); Warburton *et al.* (2003)
Sediment budgets	Blanket peat catchments	Burnhope Reservoir, upper Weardale	Holliday *et al.* (in review)
Hydrology	Blanket peat catchments	Moor House, upper Teesdale	Holden (2000); Holden and Burt (2002)
Hydrology and sediment delivery	Blanket peat catchments	Rough Sike, Moor House, upper Teesdale Trout Beck, Moor House, upper Teesdale	Crisp (1966); Burt *et al.* (1998); Evans and Burt (1998) Evans *et al.* (1999)
Channel change in upland catchments	Response to climate change and flooding	Tyne Basin, Teesdale	Rumsby and Macklin (1994)
	Response to mining	River South Tyne, Teesdale	Macklin and Lewin (1989)
	Response to climate change and mining	Swinhope, upper Weardale	Warburton and Danks (1998); Warburton *et al.* (2002)
Sediment transport	Particle dynamics; supply and transport	Moor House, upper Teesdale Carl Beck and Great Eggleshope Beck, upper Teesdale	Warburton and Demir (1998) Carling (1983)
	Channel response to flooding	Upper Weardale	Egglestone (1881); Carling (1986a & b, 1987a & b); Gifford (2000)
Integrated catchment management	Regions of upper blanket peat	Moor House, upper Teesdale	Burt *et al.* (1997)
Evaluation of environmental monitoring	Long-term precipitation and stream flow	Moor House, upper Teesdale	Burt *et al.* (1998)
Lowland floodplain analysis	Channel response to historic flooding	River Tyne	Macklin *et al.* (1992); Rumsby and Macklin (1994)
	Channel response to mining	River Wear, Tyne and Derwent River South Tyne	Macklin *et al.* (1997) Macklin and Lewin (1989)

Table 2.3 Estimate of contemporary process rates and storage for the Northern Pennines.

Component	Rate	Area	Method / Note	Source
Processes				
Soil creep	2-3 $cm^2\ yr^{-1}$	Weardale	Young Pits	Donoghue (1988)
Landslides	1200 m^3	South Tyne, Moor House	Survey	Warburton (unpublished)
Peat slides	2720 to 30750 m^3	Noon Hill, Weardale/Teesdale	Survey	Carling (1986a)
Gully erosion	560 to 1000 $t\ km^{-2}\ yr^{-1}$	Rough Sike, Moor House	Suspended load sampling	Crisp (1966)
Bank erosion	0.05 $m\ yr^{-1}$	Swinhope Burn, Weardale	Survey, reach average	Warburton (unpublished)
Bedload transport	0.33 $t\ km^{-1}\ yr^{-1}$ 0.55 $t\ km^{-2}\ yr^{-1}$	Carl Beck, Teesdale Great Eggleshope Beck, Teesdale	Bedload traps and sampling	Carling (1983)
Suspended sediment transport	24.77 $t\ km^{-2}\ yr^{-1}$ 12.07 $t\ km^{-2}\ yr^{-1}$	Carl Beck, Teesdale Great Eggleshope Beck, Teesdale	Sampling and rating	Carling (1983)
Storage Elements				
Colluvium	10^2 - 10^3 year return period 36 year recurrence interval	Noon Hill, Weardale/Teesdale North Pennines	Hillslope scars Peat slides	Carling (1986b) Carling (1986a)
Upland channels	Reworking 5 to 20 year return period	Headwaters- Tyne Basin	Climate and flood records	Rumsby and Macklin (1994)
Reservoirs	43.1 $t\ km^{-2}\ yr^{-1}$	Catcleugh, Northumberland	Reservoir survey	Hall (1967)
Lowland floodplains	Accretion, 2.4 $cm\ yr^{-1}$ Reworking >20 yr return period	Tyne Basin	Climate and flood records	Rumsby and Macklin (1994)

(Modified from Warburton, 1998)

sediment budget approach is a method that provides information on the efficiency of the sediment delivery system in terms of sources, storage and remobilisation that was previously undetermined using SDR and sediment yield estimates alone. Traditionally river monitoring was used as a method for determining catchment sediment yields. The lack of long-term stream monitoring is a limiting factor in assessing sediment yield variation over time and alternative sources of proxy data obtained from catchment sediment stores (floodplains, lakes and reservoirs) have provided an opportunity to examine the effects of historical climate and land-use changes on sediment yields from drainage basins. Establishing chronologies for recent sediments in storage using ^{137}Cs provides a valuable method for assessing sediment yield variability over time. This technique has also been useful for correlating core sediments to determine spatial variability in the distribution of sediment in lakes and reservoirs. There has been a wealth of research over the last three decades that has used ^{137}Cs to date lake and reservoir sediments. This has mainly focussed on assessing land-use change and catchment disturbance on catchment sediment delivery.

The majority of research into sediment delivery in upland regions of the UK has concentrated on quantifying sediment yields in relation to land-use change and on the geomorphological effectiveness of storm events. In the North Pennines there had been no published research using ^{137}Cs to establish chronologies for recent sedimentation and determining suspended sediment yields. There is evidence of research into linkages between components of sediment budgets e.g. hillslope sediment sources and the channel but there is yet to be a sediment budget approach evaluating sediment delivery at the catchment scale in the North Pennines.

Understanding catchment scale sediment transfer is useful in evaluating the spatial and temporal movements of contaminants to storage reservoirs. Identifying the location of potential sediment sources and assessing their sediment supply potential provides valuable information for water authorities dealing with reservoir storage capacity predictions.

CHAPTER 3 - THE PHYSICAL SETTING OF THE NORTH PENNINE REGION

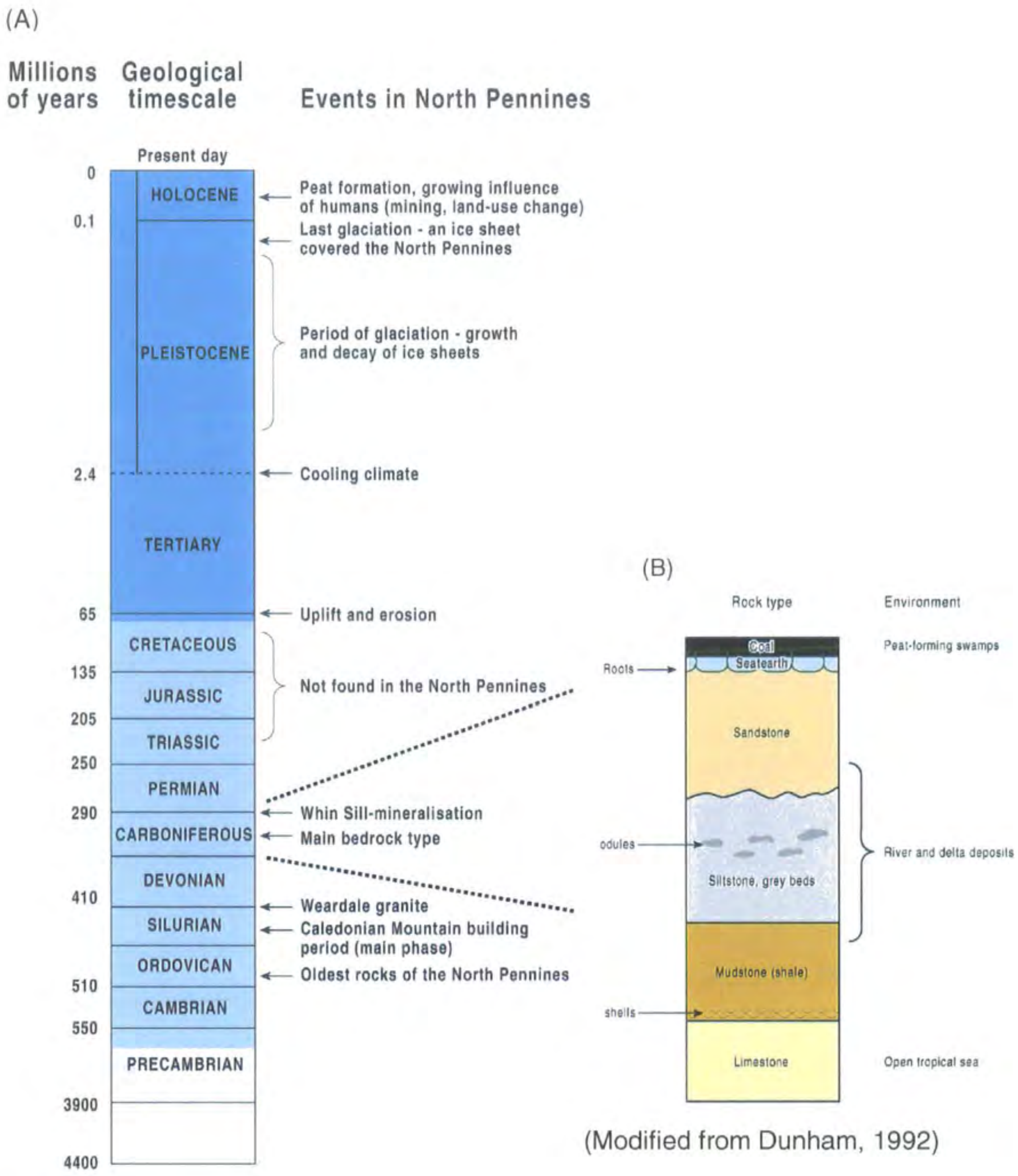
3.1 Introduction

A clear understanding of the physical setting of the North Pennine region is required as it provides a context for developing a research framework for evaluating sediment transfer in upper Weardale. Stevens and Atkinson (1970) described the general pattern of relief in this region as being one of gently sloping interfluves, interrupted by deep, relatively steep-sided dales. The topography of the North Pennines has been shaped by a series of physical processes relating to geological and climatic events, which in turn have influenced the development of a range of soil and vegetation types. The legacy of human activity in this region, through land-use change and disturbance, has further modified the landscape and determined the routes of sediment transfer within these upland systems. A brief introduction to the geology of the North Pennines is included, together with an outline of the glacial history of the region. Justification for the selection of Burnhope Reservoir as a study site is provided in line with the WARMICE project objectives. Descriptions of the physical characteristics of the main research catchments of Burnhope and Langtae are outlined and the nature of land use change, disturbance and contemporary climatic variability discussed. Discussion of regional geology, climate, topographic and soil characteristics is key in assessing likely sediment sources, sinks and transfer zones in a catchment sediment budget.

3.2 Geological history of the North Pennines

Wray (1936) describes the Pennines as the centrally dominant feature in the physiography of Northern England. The North Pennine region generally lies above 400 m, with the highest point being Cross Fell at 893 m O.D. The main rock types of the North Pennines are of Carboniferous age and were deposited between 360 and 285 million years ago (mya). Carboniferous limestone, Millstone Grit and coal layers developed together with sandstones, mudstones and shales. Figure 3.1 A represents a geological timeline of events and processes that have operated in the North Pennines from the Ordovican period from 510 million years ago (mya) to the present. This profile is simplified as processes of folding and faulting have modified the

Figure 3.1 (A) Timeline showing the series of geological events and processes operating in the North Pennines over the last 3900 million years (B) The profile of rocks from the Carboniferous system.



(Modified from Dunham, 1992)

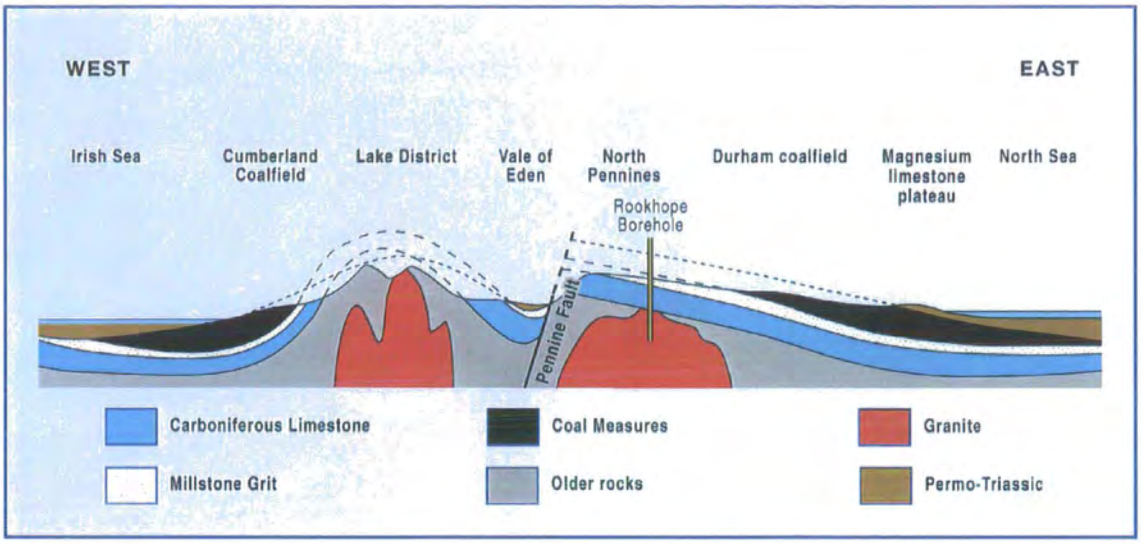
stratigraphy over time. A generalised profile of rocks of the Carboniferous system is included as an inset (Figure 3.1 B) and shows the environments in which they were deposited. Figure 3.2 shows a cross-section of the North Pennines from west to east illustrating the main rock types and structures. These figures can be referred to during subsequent discussion of the geological development of the region.

Johnson (1970) describes three periods of earth movements that have contributed to the tectonic evolution of Northern England. Each of these periods caused fracturing and folding of the rocks to form the present landscape. The earliest period was around 410 mya during the Silurian-Devonian era when the Weardale granite intruded as a major batholith underlying the central and western part of the region. This low-density granite resulted in the structure known as the Alston Block and is responsible for the regions structurally positive form from Devonian times to the present day (Johnson, 1970). This gentle intrusion caused faulting to the north, west and south. The Pennine fault to the west is shown on Figure 3.2.

During the Carboniferous-Permian interval, around 290 mya, uplift of the Alston Block occurred due to movements of basaltic magma leading to the formation of Whin Sill. The presence of Pennine faults resulted in maximum elevation being truncated and the Carboniferous beds dipping away to the north, east and south. It was during this period that mineralisation of the Carboniferous limestone, sandstones and siltstones occurred. The formation of such ores as galena, zinc, fluorite and baryte are the result of hydrothermal brines rich in calcium chloride flushing through fractures in the Carboniferous rocks (Sawkins, 1966).

Johnson (1970) describes the final stage of major earth movement as occurring during the Tertiary period (65–2.4 mya), when the structural pattern of northern England was finally modified to its present form. A period of fault movement and uplift caused elevation of the western part of the Alston Block resulting in the general easterly regional dip of the Carboniferous rocks at around five degrees (Johnson, 1970). This series of earth movements lead to the formation of the parent geology of the North Pennine region. At the end of the Tertiary period, around 2.5 mya global climatic forcing led to the modification of the geological landscape. Global cooling brought about the formation of glaciers that coalesced to form large ice sheets. This was the beginning of Pleistocene glaciation.

Figure 3.2. Geological cross-section of the North Pennines showing the main rock types and structures.



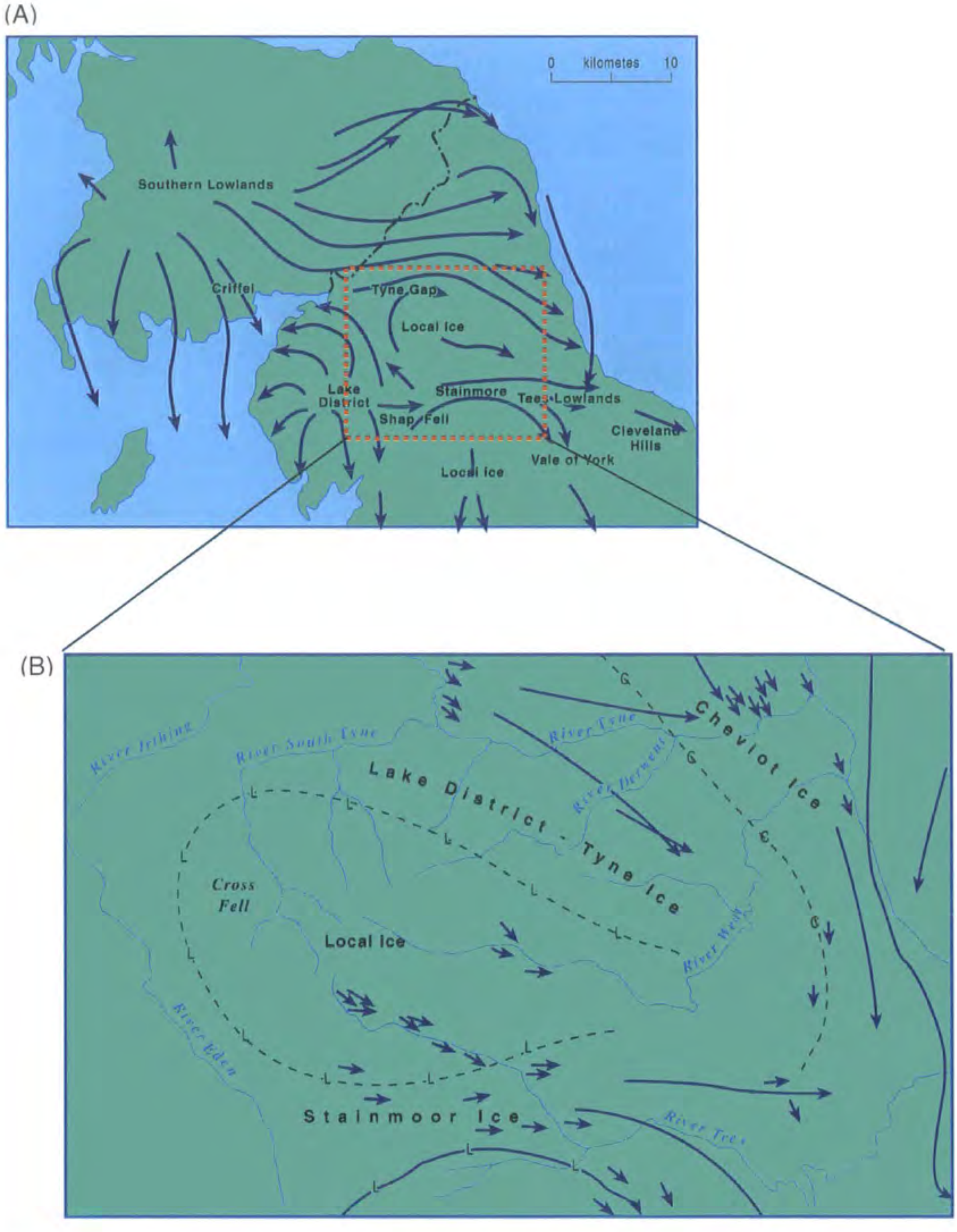
(Modified from Waters, 1976)

3.3 Glacial history of the North Pennines

Throughout the Pleistocene there were climatic shifts between cold (glacial) and warm (interglacial) episodes from the onset of the first glacial maximum to the present day interglacial (Holocene). Ice sheet formation during the glacial phases and retreat during the interglacial periods have been associated with processes that fashioned the major geomorphological features found in the North Pennines today (Moore, 1981). The main North Pennine glaciation occurred between 21-14,000 years ago (Devensian glaciation). During this time, ice sheets grew over Scotland, the Lake District and Ireland. According to Manley (1950) annual precipitation in Weardale was insufficient to maintain a snowfield large enough to generate its own ice. As a result, the local North Pennine ice source was located over the summit area of Cross-Fell to the west (Manley, 1950). Figure 3.3 A shows ice flow patterns in Northern England and Southern Scotland while Figure 3.3 B shows the local ice flow patterns in the North Pennines with ice sheet flowing perpendicular to many of the main valleys.
At the end of the last glacial period around 11-10,000 years ago, after the retreat of the late Devensian ice sheet there was a brief return to glacial conditions (Loch Lomond Stadial) and during this period there is evidence of the growth of minor cirque glaciers in parts of the North Pennines.

During the glacial periods, layers of boulder clay were smeared over the landscape in thin layers over interfluves, while deep, extensive sheets of till were deposited on the lee side of valleys with respect of ice sheet flow (Lunn, 1995). These superficial deposits of Weardale have been mapped in detail by Maling (1955) and Falconer (1970) and can be broadly classified into glacial tills, solifluctate, soils derived from colluviation or weathering and unconsolidated debris levels from mining activity. Johnson and Dunham (1963) note that at the head of the Pennine Dales, boulder clay occurs at least up to 615 m O.D. Higher ridges over 615 m O.D are devoid of superficial deposits and in such areas pedogenic processes are dependent on the lithology of Carboniferous limestones, shales and sandstones. Periglacial conditions prevailed during the latter stages of the Late Devensian and during the Loch Lomond Stadial in areas outside the glacial limit. Freeze-thaw processes eroded rock fragments while soil masses moved downhill by solifluction (Atherden, 1992). These periglacial conditions played an important role in the redistribution of older glacial deposits.

Figure 3.3 Ice flow patterns during the Devensian glaciation in (A) Northern England and Southern Scotland and (B) the local North Pennine region.



(Modified from Beaumont, 1968 and Moore, 1981)

3.4 Soils and vegetation of the North Pennines

Soil-forming processes in the North Pennine region are controlled by climate, altitude, slope gradient, surface vegetation and the permeability of soil parent material (Stevens and Atkinson, 1970). Above 615 m O.D an extensive cover of blanket peat occurs over the majority of the land surfaces and surface deposits. Research suggests that peat formation in the Southern Pennines was initiated during the Boreal-Atlantic transition (8000 BP) and that growth has increased in the last 2000 years in response to climatic deterioration (Conway, 1954). The degradation of the peat surfaces can also be attributed in part to changes in climatic conditions. Bower (1961) concluded that climate is a basic factor behind blanket peat development and degradation. Pollen analysis interpreted by Tallis (1997) suggests that desiccation of the peat surface may have occurred during the Medieval Warm Period (AD 1100-1250) and that this desiccation period may have permanently damaged the peat system as it resulted in changes in growth patterns of the peat. The peat is ombrotrophic in that it is disconnected from the mineral layers below and receives all its moisture and nutrients from precipitation. This supports the theory that the majority of peat evolution in the Pennines has been attributed to past climatic conditions as opposed to variations in parent material (Smailes, 1968).

Between 615 and 430 m O.D soil development on boulder clay and slope deposits is characterised by poorly drained, peaty gley soils with a surface horizon of amorphous peat overlying a strongly anaerobic blue/grey clay mineral horizon (Stevens and Atkinson, 1970). Podzolic soils are found where the moorland overlies free draining parent materials. These occur on steep slopes in the North Pennines on sandstone outcrops (Atherden, 1992). Some of these soils contain mineral horizons as a result of leaching and podzolisation, which will eventually become gleyed if the mineral horizons affect the drainage of the soil. The soils in Weardale form a continuum from freely draining podzols through to poorly drained peats with Peaty Podzols and Peaty Gleys dominating moorland above 615 m O.D through to Surface-Water Gleys around 413 m O.D. and Ground-Water Gleys on lower ground (Stevens and Atkinson, 1970).

The distribution of contemporary surface vegetation in Upper Weardale is related to altitude, moisture status of soil and the distribution of soil types. The length of the growing season and acidic, nutrient poor nature of the soils restrict vegetation colonization on these open moorlands. The growing season decreases rapidly with altitude, decreasing by around 13 days for every 100 metres (Atherden, 1992). Pollen diagrams published from peat deposits in the area reveal that grasses and sedges dominated an open herbaceous vegetation at the end of the Late-glacial period with the only woody species recorded being Juniper, dwarf birch and willows (Atherden, 1992). By around 8800 years ago the Juniper woodland had been replaced by birch and hazel with other species including oak, alder and elm. By 5000 years ago the oak and alder were becoming more important but forest clearance activities around 3000 years ago marked the decline in woodland on the fells (Atherden, 1992). Grasslands, heath and blanket bog now dominate the fells with species of Cottongrass, Sphagmum mosses, liverworts and Phragmities communities common on moorland, gleyed soils. On the better drained soils, Culluna heathland is prevalent, making way for mixed Calluna grassland and Sheeps-fescue on drier soils (Atherden, 1992).

3.5 Climate: temperature and precipitation in the North Pennines

The cool, cloudy and wet climate of the North Pennines has been described as 'upland maritime' due to the relatively high altitude and proximity to the sea. The range in altitude and topography influences both temperature and precipitation whilst aspect, slope and exposure control microclimates within catchments and individual valley systems. The alignment of the highest ground is orthogonal to the prevailing wind resulting in marked differences in the climate on the east and west side of the Pennines. This strong wind from the east is known as the Helm wind (Atherden, 1992). Valley alignment is also important with respect to aspect. South-facing slopes receive more sunshine than those facing north, significantly altering temperature profiles within valley systems. Atherden (1992) comments on British lapse rates being some of the steepest in the world, with a decrease in temperature of around 1°C for each 150 m gained. Comparing mean maximum and minimum temperatures from Moor House National Nature Reserve (NNR) in upper Teesdale with data from Drayton in Warwickshire (both Environmental Change Network (ECN) monitored sites, from http://www.ecn.ac.uk/Database/index.html) provides an example of the effects of altitude and latitude on temperature in Britain. There is a maximum temperature range of 16.4 °C at Moor House from -1.1°C to 15.3°C. The temperature range in Drayton is 20.9 degrees varying from 1.8°C to 22.7°C. The mean winter temperatures in Drayton do not drop below freezing while at Moor House, mean minimum temperatures are below freezing from December to March.

Rainfall is closely linked to topography in Britain, as most rain falls as a result of cooling of air as it is forced to rise over high ground (Atherden, 1992). As the dominant rainbearing winds are South-Westerlies and the Pennines form the central land mass of Northern England, annual rainfall totals of up to 2000 mm per year are common. Table 3.1 shows the mean monthly maximum and minimum temperatures and mean monthly rainfall totals recorded at Moor House NNR from January 1992 to December 2001. Mean monthly rainfall varies from 84.2 mm in June to 287.5 mm in February. The overall low temperatures and persistent levels of precipitation result in snowfall in the uplands while the short periods of sunshine increase residence time of snow cover. The mean number of days of snow lying at Moor House from 1931 to 2000 was recorded as 65 while the maximum number of consecutive days with snow lying was also 65 recorded between 1st February and 5th April 1969 (Holden and Adamson, 2001). These climatic conditions promote shorter growing seasons leading to slow re-colonisation of exposed and disturbed ground (Smithson, 1985) that are prone to frost action processes common during the winter months. Average rainfall and temperature data for Weardale are discussed in more detail in section 3.8.

3.6 Site selection

The logistics of site selection were controlled by the objectives of the WARMICE project proposal. The choice of the focus catchment was dependent on developing methods for modelling sediment transfer from previously un-gauged catchments. The sediment-monitoring framework involved intensive sampling of stream suspended sediments and a coring strategy for extracting consolidated reservoir sediments. The success of the project was reliant on a number of practical issues, including site access for the installation of monitoring equipment in the reservoir and catchment. The most important consideration of all was the issue of reservoir operations. If the reservoir had been significantly drawn-down for maintenance purposes, dredged or scoured (a common practice to cope with sedimentation problems) then the reservoir sediment archive would not be a true representation of geomorphological processes occurring in the catchment. The site of Burnhope Reservoir in Upper Weardale satisfied the above criteria. Access was granted and no mechanical removal of reservoir sediments had occurred.

The site of Burnhope Reservoir was chosen as it was considered representative of small storage reservoirs in the North Pennines constructed on Carboniferous shales and limestones in the early 20th century (Kennard and Knill, 1968). The catchments of Burnhope and Langtae that directly feed the reservoir are typical of small drainage basins in upper Weardale, located on Carboniferous geology with stream channels

Table 3.1 Mean monthly temperatures and rainfall totals from Moor House National Nature Reserve (NNR) in the North Pennines.

	Mean max temperature (°C)	Mean min temperature (°C)	Mean rainfall (mm)
January	3.0	-1.1	190.3
February	3.4	-0.7	287.5
March	4.3	-0.5	212.4
April	6.8	0.7	157.1
May	11.0	2.8	102.0
June	13.4	5.7	84.2
July	15.3	7.8	109.1
August	15.1	7.7	112.3
September	12.3	6.2	149.4
October	8.8	3.8	182.1
November	5.5	1.2	238.1
December	3.1	-1.1	219.2
Annual (mean)	8.5	2.7	170.3

All data from ECN (Environmental change network, http://www.ecn.ac.uk/Database/index.html) actively eroding Devensian glacial tills. Land use practices typical of the North Pennine catchments include mining, grazing and forestry and these are represented in the direct catchwaters feeding Burnhope Reservoir. Investigations into the sediment delivery system in the Burnhope and Langtae catchments through the construction of a sediment budget is therefore considered representative of other catchments in the North Pennine region.

3.7 The study catchments: Burnhope and Langtae

Burnhope Reservoir (NY 5388 3845) is located on Burnhope Burn, an upper tributary of the river Wear (Figure 3.4). It is a multi-source reservoir fed by the main Burnhope (11.8 km^2) and Langtae (3 km^2) catchments to the west and a number of smaller tributaries (3 km^2) that together constitute a direct catchwater area of 17.8 km^2. Additional water sources increase the catchwater area to 27.9 km^2 and feed the reservoir via pipelines from the Wellhope catchment in the north and from Ireshope Burn, West Grain and Daddry Shield catchments to the south. Tables 3.2 and 3.3 provide a summary of the characteristics of Burnhope Reservoir and catchments areas of the direct and indirect catchwaters. Altitudes in the catchment vary from 746 m O.D at Burnhope Seat on the Wear–Tyne interfluve to 400 m O.D at the dam wall. The reservoir has an area of 0.8 km^2 and a maximum depth of 30 m at full capacity. Burnhope and Langtae Burns are complex fluvial systems composed of bedrock and boulder-bed channels. Both streams drain catchments comprised mainly of a Carboniferous geology of shales, limestone and sandstones. The solid and drift deposits in the study catchment are shown in Figure 3.5. The majority of deposits on the upper slopes of the catchments consist of Middle Limestone Group deposits with Firestone Sill (of the Upper Limestone Group) evident towards Burnhope Seat. A soliflucted grey boulder clay layer overlies this Carboniferous bedrock, which is evident at a number of sites along eroded banks and stream-side scars in the catchment and as a result of artificial drainage ditches dug at the base of hillslopes around the reservoir (Kennard & Knill, 1968).

Table 3.4 describes catchment characteristics related to drainage and relief. Drainage density and slope of upland areas are both influenced by basin relief (Gordon *et al.*, 1992). Langtae, the smaller of the two catchments, has slightly steeper relief that is reflected in the mean stream slope values. Average channel slope is one of the factors controlling stream velocity but with mean flow discharges of 0.22 and 1.04 $m^3 s^{-1}$ for

Figure 3.4 Location map of (A) Upper Weardale and (B) direct catchment areas of Burnhope and Langtae flowing into Burnhope Reservoir.

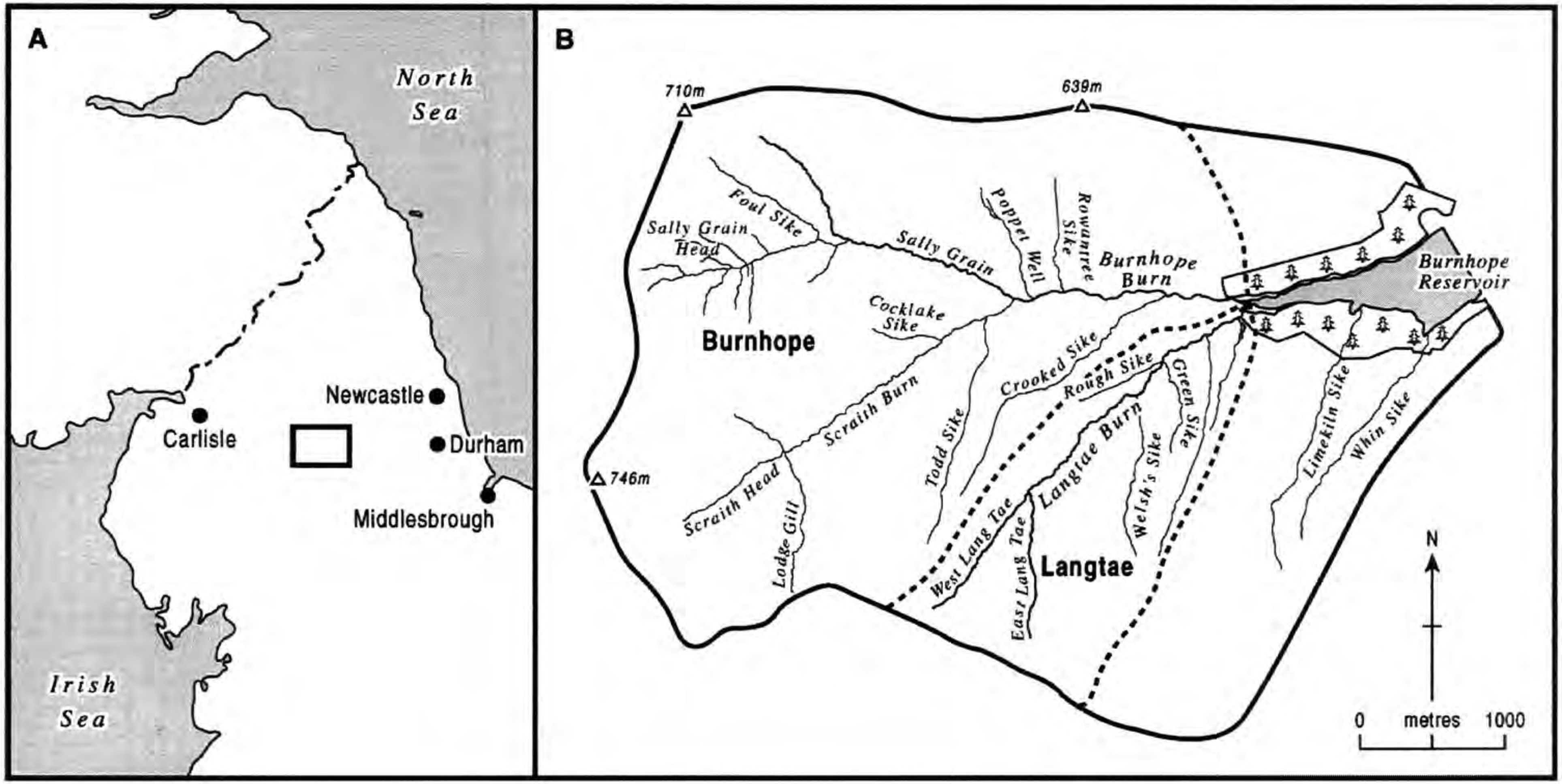


Table 3.2 Characteristics of Burnhope Reservoir.

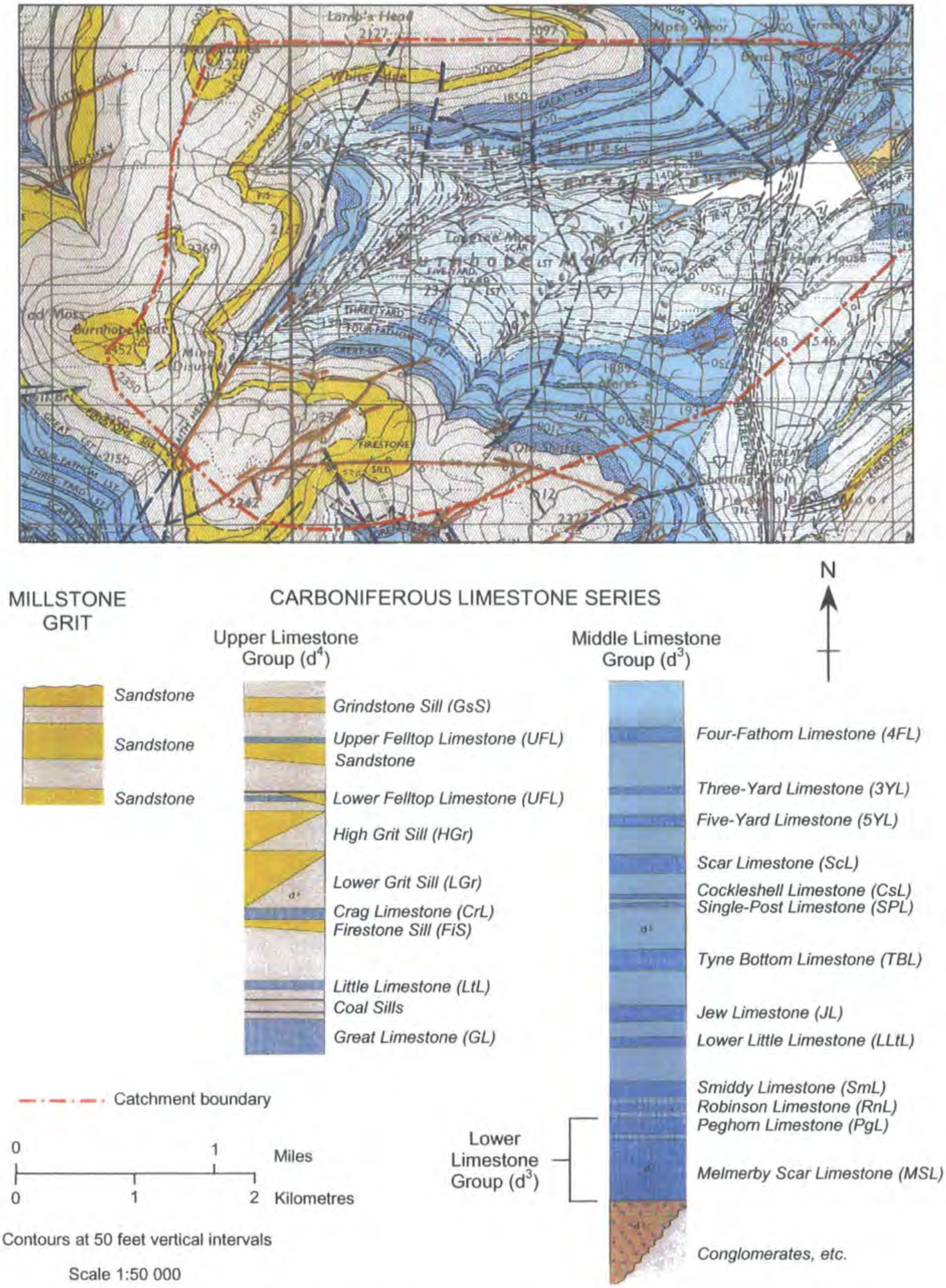
Characteristics of reservoir operations	
Date of impoundment	1936
Reservoir capacity (mega litres)	6445
Top water area (km^2)*	0.8
Annual outflow (1992) (mega litres)	5101
Reservoir trap efficiency (%) **	92
Direct water catchment area (km^2)	17.8
Indirect water catchment area (km^2)	27.9

*Allderidge (1935)
** Based on curves of Brune (1953)

Table 3.3 Direct and indirect catchments feeding Burnhope Reservoir.

Catchment	Area (km^2)	Individual catchments	Area (km^2)
Direct	17.8	Burnhope	11.8
		Langtae	3.0
		Others	3.0
Indirect (via pipeline)	27.9	Wellhope	8.3
		Ireshope Burn	7.5
		West Grain	7.9
		Daddry Shield	4.2

Figure 3.5 Solid and drift geological deposits of the Burnhope catchment.



Sourced from British Geological Survey (BGS) England and Wales Sheet 25, Solid and Drift Edition 1:500 000 series - Alston

Table 3.4 Table of relief, drainage and flow characteristics for Burnhope and Langtae catchments.

Catchment characteristics	Burnhope	Langtae
Area (km^2)	11.8	3.0
Total stream length (km)	17.5	9.9
Stream pattern	Dendritic	Dendritic
Relief Ratio (R_r)	0.06	0.07
Mean annual flow ($m^3 s^{-1}$)	1.04	0.22
Drainage Density (R_D)	2.16	2.30
Average stream slope (m/m)	0.053	0.079

Langtae and Burnhope respectively it is clear that catchment area is another important controlling factor on flow. Both catchments have dendritic drainage patterns and are dominated by surface runoff, which is a function of the relatively uniform geology of these catchments. Drainage densities are high with 2.30 and 2.16 km^{-1} in the Langtae and Burnhope catchments respectively. This reflects the finely divided network of steeply sloped streams with short lengths that are characteristic of these upland drainage basins.

The soils of the study catchment vary with altitude ranging from Cambric stagnogley soils on the lower slopes to raw Oligo-fibrous peats in the upper catchment. Table 3.5 lists the soil groups and sub-groups determined from the Soils map of Northern England (1990) and Atkinson (1968). Blanket peat dominates the slopes above 600 m O.D with surface and ground water gleyed soils on the lowest slopes (400-500 m O.D). Peaty gleyed soils are dominant on the middle catchment slopes (500-600 m O.D) with gleyed podzols and basin peat and blanket peat making up the remaining soil coverage. The catchments are moorland areas used predominantly for sheep grazing and grouse shooting. Air photographs have been used to assess the extent of blanket peat coverage in the catchments. Peat occurs extensively in both catchments, consisting of 'haggs' dissected by gullies. Blanket peat cover is more extensive in the Langtae catchment (58% of the catchment area), with incised gully systems on both the north and south facing sides of the channel and at the head of the stream network. Peat coverage is less extensive in the Burnhope catchment (43%) with incised gullies coupled to the channel only at the very head of the stream network and at a small section on the north facing side of the channel further downstream. The gullies are in various stages of re-vegetation. The areas of Langtae and Burnhope that are now void of blanket peat could be described as being in this terminal phase of peat erosion and areas that once supported blanket mire have now been re-vegetated by bracken. The dominant contemporary vegetation on the blanket peat is sedge with bilberry and heather overlying the hagged peat. Where peat haggs are coupled with the channel, the channels are steep sided and cut into bedrock exposing glacial till and solifluction material.

Table 3.5 Soil types and sub-groups in the study catchments.

Catchment slopes	Soil type	Soil sub-group
Lower (400-500 m)	Cambric stagnogley	Surface water gley (80%) Ground water gley (20%)
Middle (500-600 m)	Cambric stagnohumic gley	Peaty gley (40%) Blanket peat (30%) Podzol with gleying (10%) Basin peat (10%) Peat gleyed podzols (10%)
Upper (>600 m)	Raw Oligo-fibrous peat	Blanket peat (90%) Podzol with gleying (10%)

3.8 Land use change and disturbance in the Burnhope and Langtae catchments from the Post-glacial period (10,000 – 4000 BC) to present

In the North Pennine region, there is evidence of human activities since the early to middle Post-glacial period (10,000 to 4000 BC) when hunter-gather cultures dominated (Atherden, 1992). The decline of elm trees during the Neolithic period (4000-1850 BC) has been attributed to the introduction of farming practices and shifting cultivation (Atherden, 1992). Metal extraction began around 1850 BC, which lead to a significant increase in population of the Pennine uplands (Dunham, 1981). There is evidence of mixed agricultural practices in valleys with grazing on high ground. Large-scale clearance of woodland in the region took place during the Iron Age and continued into the Roman period. By the end of the Roman occupation in the fifth century, all Pennine woodlands had been cleared (Atherden, 1992).

Change and disturbance over the past two hundred years in upper Weardale has been both periodic and continuous in nature. Methods of land management have been refined over time but it must be remembered that the most recent disturbance mechanisms are the latest in a long series of changes over the last 10,000 years. Figure 3.6 is a timeline diagram that outlines the temporal scale of human activities for the past two hundred years, ranging from periodic disturbances of afforestation, block clear-felling and mining to the continuous pressures from sheep grazing. Each of these activities have left an imprint on the soil, vegetation and morphology of North Pennine catchments and therefore modifying the routes of sediment transfer through the drainage systems. Figure 3.7 is a general conceptual model for an upland catchment that has been modified to account for processes of catchment disturbance in sediment routing from the hillslope to the reservoir. This model can be referred to throughout the discussion of the influences of various catchment disturbances on sediment transfer through the system. A distinction between periodic and continuous disturbance activities occurring in the Burnhope and Langtae catchments are discussed below.

3.8.1 Periodic disturbance

Periodic disturbances, including mining and afforestation, are relevant when addressing issues of sediment supply in the Burnhope catchment. Mining is important when assessing the nature of sediment routing and storage within the channel that is dominated by channel bed and bank supply. Erosion of mining waste deposited in the channel and on floodplains together with reworked contaminated deposits from stream-

Figure 3.6 Timeline of disturbance and human activities occurring in the Burnhope and Langtae catchments over the past 200 years.

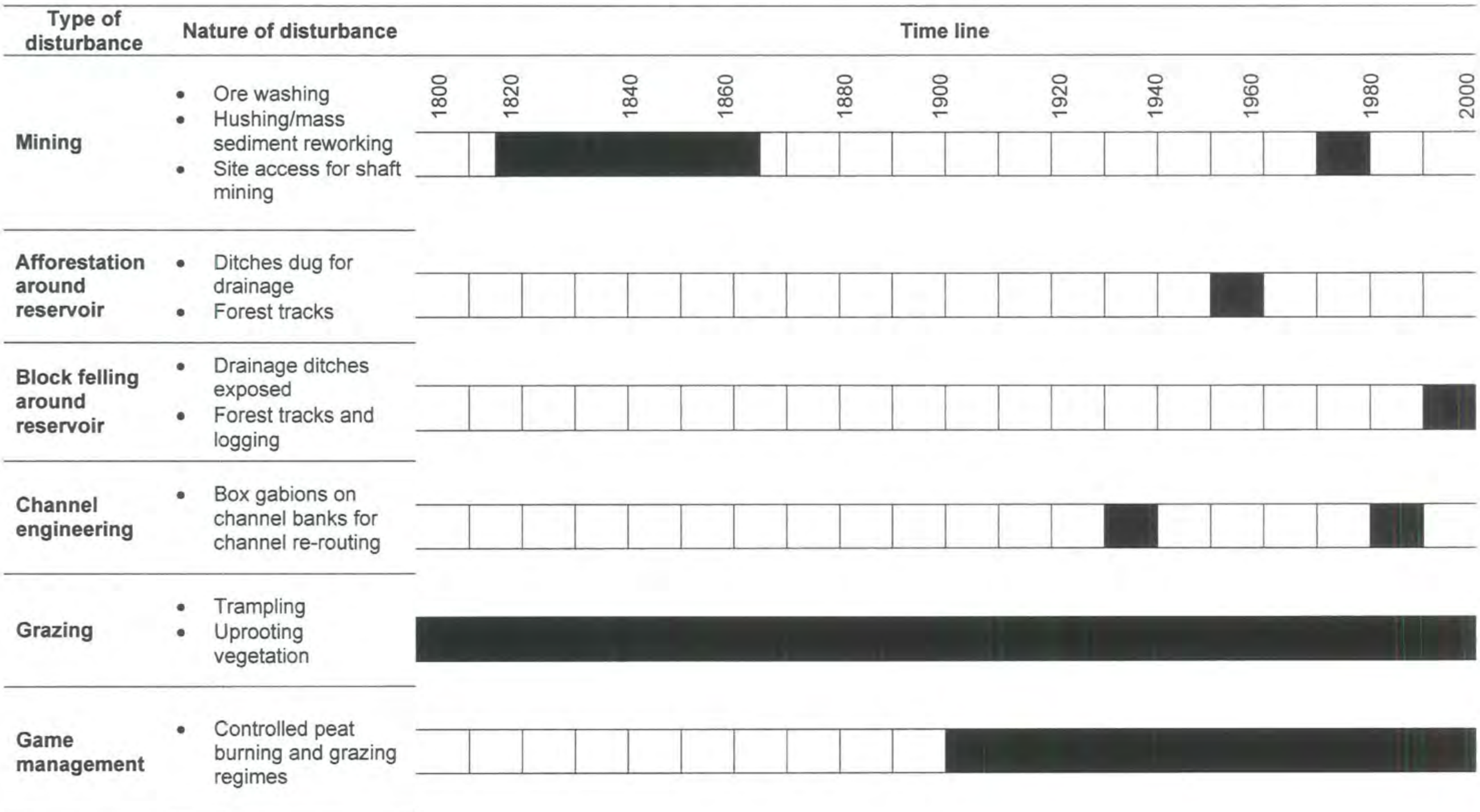
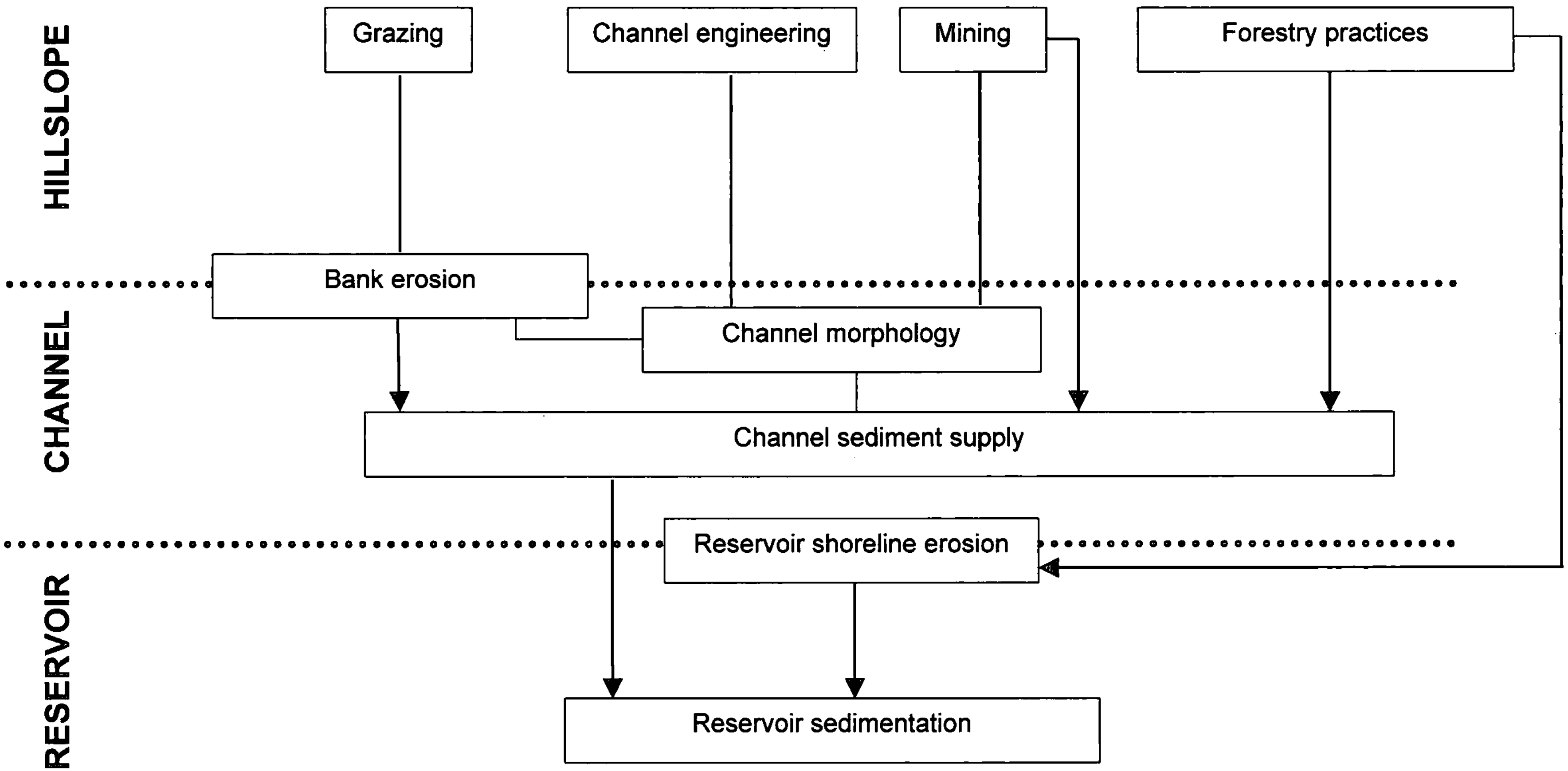


Figure 3.7 General conceptual model summarising the impacts of catchment disturbance on sediment delivery to Burnhope Reservoir



side scars are potential sources when coupled to the channel (Figure 3.8).

There is a long history of mining in the North Pennines that began in Roman times and finally petered out in the early 20th century (Warburton, 1998). The industry reached its peak in the 18th and the first part of the 19th century after which the majority of mining ceased, with only the richest companies continuing work into the early 20th century (Dunham, 1981). The physical remains of mining and related industrial activities are apparent today as shown in Figure 3.9. These mine tailings were left over from the crushing and washing processes and remain un-vegetated at the head of the Burnhope and Langtae catchments. The majority of activity in the North Pennine ore fields was underground shaft mining (Dunham, 1981). There are, however, a number of examples of surface exploration using hydraulic mining methods. These methods have altered catchment hydrology and morphology by widening tributary valleys through hushing, shifting large volumes of rock to the channel margins that is presently reworked during flood events and stored in channel bars and floodplains.

Hushing is method of hydraulic mining that began in the 16th century with the introduction of the latest technology to expose mineral veins (Dunham, 1981). It involved the building of earth dams and impounding large quantities of water on the fell sides that was periodically released, flushing soil, rock and ore into the channel (Dunham, 1981). Dunham (1981) reported that an estimated 2.6 million tonnes of rock have been removed by this process at Coldberry Gutter in upper Teesdale and much of this material was transported downstream to the River Tees. Hushing caused localised river aggradation and channel planform change along with mine tailings being the source of heavy metal contamination. The large volumes of sediment washed from valley sides during the hushing process at Burnhope and Langtae are stored on channel margins. Figure 3.10 shows a tributary channel of Burnhope Burn drastically widened by the scouring of rock and deposition of mining spoils at the tributary head. A channel bar is evident at the confluence of the tributary and the main channel, evidence of mining sediments altering flow patterns. From air photographs taken over the catchments paleo-channels are evident that could be relic features of such channel planform changes.

Figure 3.11 is a map of mineral deposits in the Burnhope and Langtae catchments showing the location of mines, mineral veins and faults and Table 3.6 total yields mined from specific mines in the Burnhope Reservoir catchment. The majority of mining was for lead concentrates that occurred in the headwaters of both catchments. In the

Figure 3.8 Mining waste deposited in the headwater reaches of North Pennine catchments provide sources of sediment to the channel.

Figure 3.9 Spoil heaps at the head of the Burnhope catchment, relic features of the mining era.

Figure 3.10 A tributary of Burnhope Burn altered by mining processes of hydraulic flushing and erosion to form a hush.

Figure 3.11 Extent of mineral deposits with location of mines, mineral veins and faults in the Burnhope Reservoir catchment.

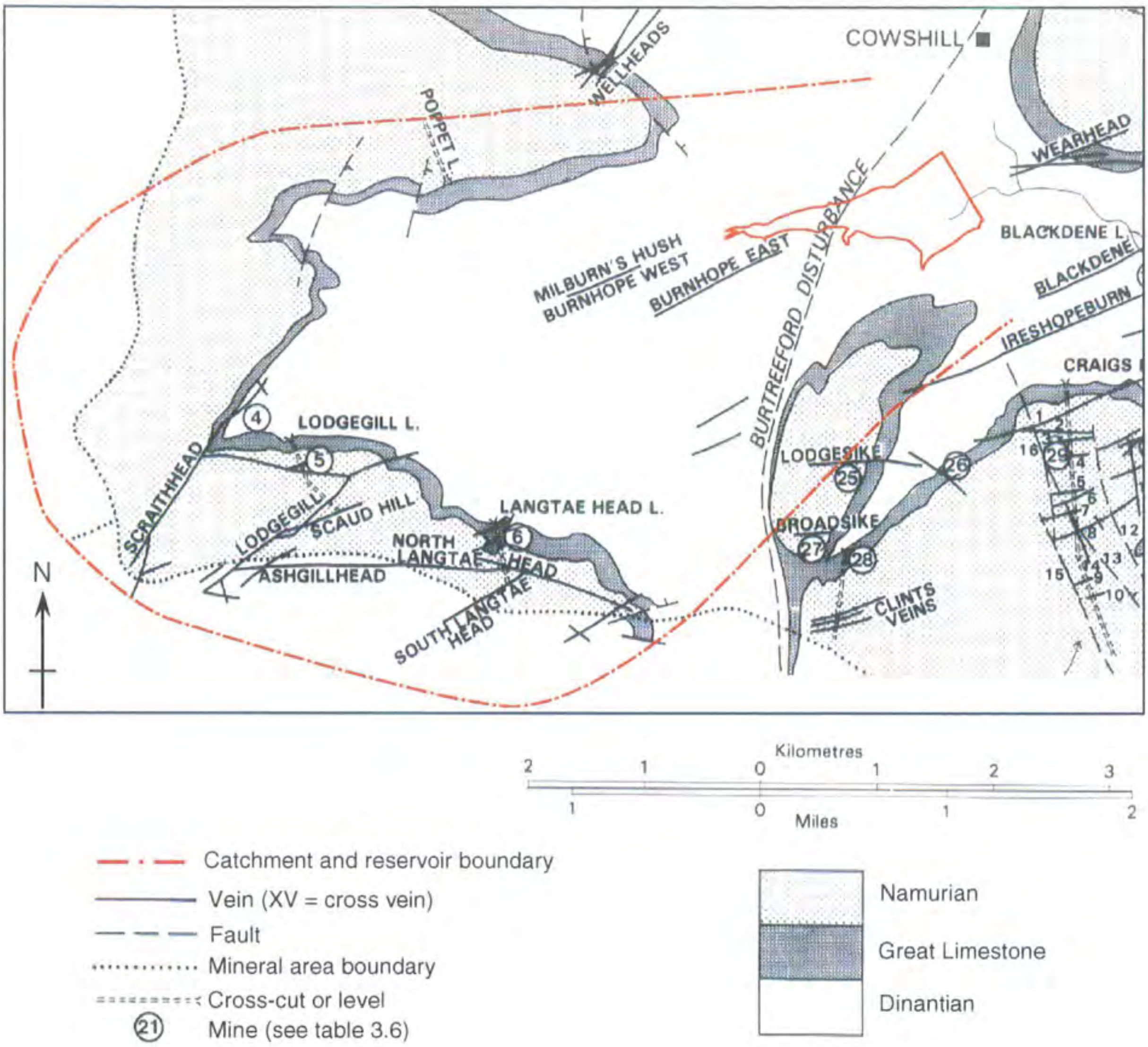


Table 3.6 Total yields of lead concentrates mined in the Burnhope Reservoir catchment.

Mine	Mining dates	Yield of lead concentrates (tonnes)
(4) Scraith Head	1818 to 1847	7705
(5) Lodgegill	1846 to 1871	11306
(6) South Langtae Head	1818 to 1860	2002

Burnhope valley, west of the Burtreeford Disturbance the lowest beds in Weardale were exposed (Dunham, 1990). Lodgegill mine was the most productive of the remotely situated mines in the Burnhope headwaters yielding 11306 t of galena between 1846 and 1871 when the mine closed (Dunham, 1990) (Table 3.6). Scraith Head and South Langtae Head produced 7705 and 2002 t of lead concentrate, respectively. South Langtae Head was the last of the three mines to close in 1860.

Afforestation around the Burnhope reservoir shoreline began in the early 1950s and a series of channels were dug under the forest cover for drainage purposes. Seedling conifer trees were planted in 15 m^2 blocks on the north and south sides of the reservoir and the whole planting procedure took between seven and eight years to complete (Pattinson, 2000). Figure 3.12 shows the extent of this afforestation around Burnhope Reservoir (0.85 km^{-2}). Fielding & Howarth (1999) state that afforestation in these upland areas often involves the introduction of mainly high-density plantations of single aged, monocultures typically of foreign origin. Between 15 and 20 years after these species are introduced, the trees develop thick canopies and have detrimental effects to the woodland floor that can no longer support vegetation (Fielding & Haworth, 1999). This results in large expanses of exposed forest ground un-vegetated by undergrowth.

Extensive clearfelling in the Wellhope catchment, to the north of Burnhope took place in 1997. Problems arose in 1998, when 'bad water' was noted to be flowing into the reservoir from the Wellhope catchment inlet pipe on the north side of the reservoir (Pattinson, 2000). The inflow pipe is located 12-15 m below the reservoir dam and a small amount of sediment was deposited directly on the reservoir bed (Pattinson, 2000). These problems were attributed to the clear-felling process as large volumes of sediment were activated with the removal of trees and erosion of newly exposed unvegetated sediments. Previously vegetated ground is likely to have been disturbed by logging vehicles and equipment and the resulting sediment laden runoff piped directly to the reservoir.

Clear-felling of the trees around Burnhope Reservoir began in 1992-1993. They proceeded to cut down the trees in blocks, in a similar way as they were planted. This was only carried out on a small scale until the problems of extensive clear-felling in the Wellhope catchment were evident and plans to clear the rest of the forest were postponed. This small-scale clear-felling is important for the stability of the reservoir shoreline as the removal of trees increases the susceptibility of the banks to erosion by wave action and freeze-thaw processes. These are not the only examples of sediment activation due to clearfelling in a Pennine reservoir catchment. Austin and Brown

Figure 3.12 Extent of plantation forest cover around Burnhope Reservoir.

(1982) and Burt *et al.* (1984) reported high suspended sediment inputs to the Holmestyes Reservoir due to excavation of forest ditches above the reservoir in 1980. Turbidity readings were noted to have increased from 2 formazin turbidity units (FBU) to 1000 FTU.

Periodic strip burning of moorland heather takes place to maintain breeding grounds for grouse. Conway and Millar (1960) compared peak flows between burnt and non-burnt catchments at Moor House in upper Weardale. They found higher peak flows in the burnt catchment where storage capacity of the soil had been altered due to severe temperatures. In the Burnhope and Langtae catchments, strip burning may affect runoff from the peat surface although the burning boundaries are not close to channel margins.

3.8.2 Continuous disturbance

Continuous disturbance such as grazing and game management directly influence vegetation species and density that in turn governs the amount of exposed soil susceptible to erosion. In terms of sediment routing to Burnhope Reservoir, sources linked to the channel network are of the greatest importance. Awareness of the pressures on these riparian zones is crucial when considering sediment supply to the channel.

The early Medieval period was one of particularly heavy grazing with large herds of cattle and flocks of sheep roaming upland catchments (Atherden, 1992). Since this period the moorland areas of Langtae and Burnhope have been used primarily as rough grazing but are being increasingly utilised as grouse moors. The successful dual-use of these areas requires careful management to maintain sheep numbers whilst protecting vegetation (Wilson, 1991). Sheep grazing results in vegetation trampling in riparian zones that interferes with the natural stability of channel banks. Sheep are often found sheltering in stream bluffs that exerts pressure on banks and promotes erosion of exposed sediment. In general, grazing appears to play an indirect, minor role in the routing of sediment in channels, but the prolonged nature of this type of disturbance and its influence on the sensitive balance of vegetation within the catchment means it is an important general influence on sediment delivery. There is no quantitative information available on stocking levels in the Burnhope and Langtae catchments but information from local farmers suggests that stocking levels have remained reasonably consistent over the past 50 years.

3.9 Local climatic variability: temperature and precipitation in the Burnhope and Langtae catchments

Mean monthly maximum and minimum temperatures and rainfall totals from a gauging site in the Burnhope catchment for the period 1992-1999 are shown in Table 3.7. The mean minimum temperatures are around freezing from December through to February. These three months fluctuating around freezing temperatures will promote the action of frost that plays an important role in sediment preparation in upland catchments. The mean average number of frost days in the Burnhope catchment from 1992-99 was 60. From observation, the action of frost processes on areas of exposed sediment, on river- banks and on the shoreline of the reservoir generates sediment and organic inputs to the system. Frost heave was greatest in silty sediments.

Mean monthly rainfall totals vary from 40.9 mm in June to 155 mm in December. The June mean total is approximately half that monitored at Moor House NNR over the same period (Table 3.1). Mean monthly rainfall at Burnhope is 60 % less than that measured at Moor House. Based on data from 1936-98, the mean total annual precipitation for the Burnhope catchment is 1287 mm but varies considerably, with 897 mm and 1786 mm recorded for 1971 and 1954 respectively. Rain occurs on an average of 216 days between 1936-98, varying between 173 and 263 days. These values of mean annual rainfall are lower than those monitored in other areas of the North Pennines. Smithson (1985) reports mean totals of 2010 mm for Moor House (290-848 m O.D) in upper Teesdale between 1941-70. These higher values highlight the influence of altitude on precipitation totals within the region.

Occasional heavy orographic precipitation from the east can result in heavy snowfalls on the northeastern slopes of the Pennines (Smailes, 1968). The number of days of snowfall and the amount of snow cover is difficult to monitor accurately as daily observations are required. There was no direct way of distinguishing snowfall from other types of precipitation within the Burnhope catchment. From comparing the mean monthly precipitation totals for the Burnhope catchment it is evident that the highest precipitation levels occur during the months October to March when temperatures fluctuate around freezing. In the Burnhope catchment in 1992, there were 32 days that recorded temperatures of below 0 °C and any precipitation falling during this period is likely to have fallen as snow.

Table 3.7 Mean monthly temperature and rainfall totals for the Burnhope catchment (1992-1999).

	Mean max temperature (°C)	Mean min temperature (°C)	Mean rainfall (mm)
January	3.5	0.3	153.7
February	3.9	0.1	139.9
March	5.7	1.9	111.0
April	8.8	3.0	54.4
May	12.9	5.2	75.6
June	15.4	8.4	40.9
July	19.7	9.7	54.9
August	18.5	9.4	78.5
September	16.0	6.6	84.0
October	10.3	2.9	124.6
November	7.1	1.4	140.2
December	5.2	-0.6	155.0
Annual mean	10.0	4.4	101.1

3.10 Chapter summary

The drainage basins of Burnhope and Langtae are characteristic of small (<100 km^2) upland Pennine catchments with fluvial systems composed of bedrock and boulder-bed channels. The catchments comprise mainly of a Carboniferous geology of shales, limestones and sandstones with a soliflucted grey boulder clay layer overlying this bedrock. The soils are mainly peaty podzols and peaty gleys and these nutrient poor soils support common moorland vegetation of sphagnum mosses, liverworts and phragmities. The high drainage densities in Langtae and Burnhope reflect the finely divided network of steeply sloping streams with short lengths that are characteristic of North Pennine upland drainage basins. The high mean annual rainfall totals characteristic of the 'upland maritime' climate coupled with the steep relief of these catchments results in flashy flood hydrographs with high peaks and short durations. There has been evidence of human activities in the North Pennine regions since the early to middle Post-Glacial period (10,000 to 4000 BC) and over time the introduction of shifting cultivation farming practices and metal mining have resulted in large-scale clearance of woodland and modification of channel systems with processes of hydraulic mining. The legacy of mining from the early to mid 1800s is still apparent in the upper tributary channels of Burnhope and Langtae with mining waste deposited in floodplains and tributary streams widened through surface extraction of ores using hydraulic mining methods. Mining in these catchments ceased in the early 20th century and the majority of these mining features have stabilised through re-vegetation. In the last 100 years land use and disturbance has been minimal with periodic, local events of afforestation and block clear-felling around the reservoir, and two short phases of channel engineering which are all noted as having minimal effect on sediment supply to the channel. These catchments have been grazed for the past 200 years but there are no records available to determine variations in the intensity of grazing over this period. Reports from local farmers indicate that there has been negligible variation in land use over the past 50 years. In summary there has been negligible variations in land use over the past 67 years since the impoundment of Burnhope Reservoir. The drainage basins of Burnhope and Langtae are characteristic of those of the North Pennine region.

This chapter has provided information on the physical characteristics of the North Pennine region, with special reference to the study catchments of Burnhope and Langtae in upper Weardale. The geology, soil, vegetation and topography have been discussed together with the climatic and human forcing mechanisms responsible for modification of the North Pennine landscape over time. This information on the physical evolution of the region is valuable for evaluating upland sediment budgets, providing context for studying the sediment transfer system of Burnhope and Langtae catchments.

CHAPTER 4 - FIELD DATA COLLECTION AND LABORATORY TECHNIQUES

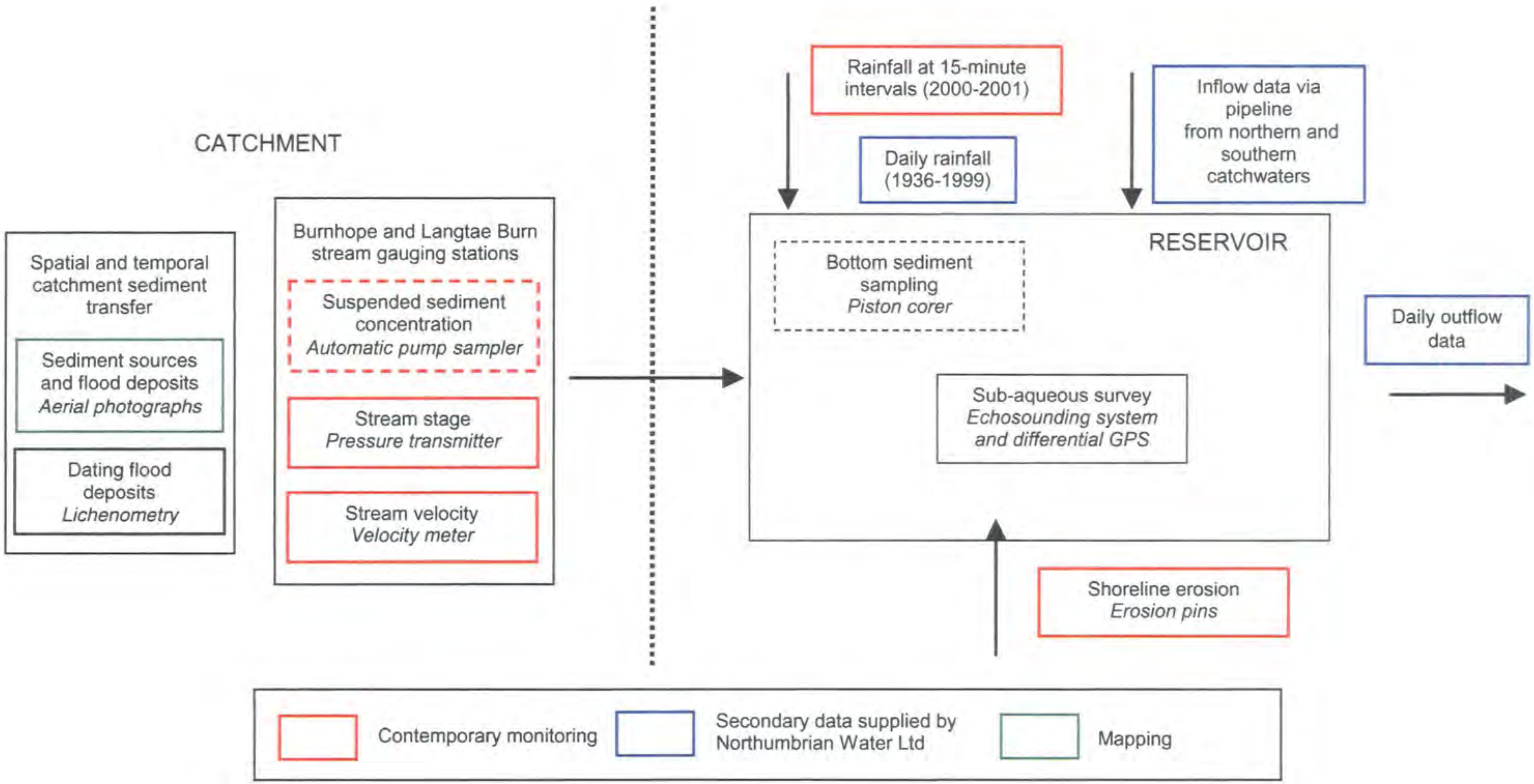
4.1 Overview of the measurement and monitoring framework

The aim of the field and laboratory-based elements of this research is to develop a measurement and monitoring framework to assess sediment transfer using a sediment budget approach in the previously un-gauged upland catchments of Burnhope and Langtae. The research considers sediment transfer at the catchment scale and the data collection framework incorporates monitoring techniques that investigate sediment movement on storm event and annual timescales. Reconstruction of the reservoir sediment history provides estimates of long-term sediment yields, while rapid assessment of catchment sediment sources and analysis of flood deposits provides insight into the timing and magnitude of sediment transfer.

The comprehensive data capture framework includes secondary data records and the collection of primary data. Figure 4.1 shows the data collection strategy in the sediment budget framework. This diagram highlights the links between various methods of data collection used, assessing sediment delivery to Burnhope Reservoir. The coloured boxes indicate different methods of data collection while the hashed boxes indicate components that required further laboratory analysis to complete the data collection process. The field techniques used include quasi-continuous monitoring and periodic sampling. Burt (1994) provides a concise review of the concepts of monitoring the environment as a whole and poses the question of monitoring as a 'perceptive science' or a 'mindless exercise'. He concludes that monitoring is the process by which we keep the behaviour of the environment in view and comments on how it provides valuable information on system dynamics in space and time. For each individual parameter, it is necessary to consider the optimum monitoring and sampling strategy to obtain the most representative data on timescales and magnitude of sediment transfer.

The following sections describe and justify the measurement of each parameter in Figure 4.1, outlining the strategies of site selection for monitoring and sampling. The series of laboratory procedures used to characterise suspended sediment yields from

Figure 4.1 Data collection strategy used in assessing sediment delivery to Burnhope Reservoir in a sediment budget framework.



fluvial monitoring and reservoir sedimentation are outlined together with a detailed overview of the methodology behind radiometric dating of reservoir sediments.

4.2 Catchment-based monitoring and data collection

4.2.1 Suspended sediment sampling

The relationship between suspended sediment and discharge provides information on the delivery of sediment to the reservoir system. This section discusses the selection of the most appropriate suspended sediment monitoring technique for upland peat catchments.

There are a number of advantages and disadvantages inherent in the application of different methods of monitoring. Wren *et al.* (2000) conclude that each researcher must decide what technique to use in the measurement of suspended sediment in fluvial environments and this will be based upon budget constraints and the desired quality of data. When considering sediment monitoring it is firstly important to consider the nature of sediment transported within the channel. Fine suspended sediment (< 63 μm) tends to be well-mixed across the cross-section of the stream but sand however is not (Wren *et al.*, 2000). The transport of sand varies in both time and space, while organics tend to float on the surface of water. Both points are important to address when monitoring sediment transport during storm events. This issue of variations in the transport of mineral and organic fractions is most poignant when considering point-sampling strategies. Problems of spatial error are common in the more traditional point sampling methods, including manual bottle and pump sampling, but also seem relevant to most of the more recent indirect methods of monitoring. Although particle size was not determined in this study and only sediment concentration was recorded, the research of Carling (1983) on a similar stream in the North Pennines provides an insight into particle size variation in suspension in these upland streams. He reported that some fine sands were found but the majority of the inorganic material was coarse silt. There were increases in grain size that corresponded to the occurrence of flood peaks (Carling, 1983).

Methods of point-integrated sampling are available and can be used to combat some of the issues of spatial error. This involves measuring sediment transfer at a number of points across the stream cross-section and at points of varying depth. With the flashy nature of flow in upland systems and the requirements of event sampling, the integrated method is not feasible. The techniques chosen need to be reliable and also applicable to the fluvial environment. The use of turbidity meters in upland catchments is problematic due to clogging of the sensors with organics. The range of particle sizes recorded by turbidity meters in these peat catchments limits the production of a reasonable calibration curve (Johnson, 1992). This leaves the methods of bottle and pump sampling. These are both accepted techniques and despite the poor temporal and spatial resolution, provide the most reliable and applicable techniques to upland systems. Bottle sampling alone is labour intensive and restrictive in terms of event monitoring.

There appears to be a wealth of research and recommendations in the literature for suspended sediment sampling in river basins but little mention of small headwater catchments (Johnson, 1992). There is a lack of consistency in sampling strategies resulting in problems in comparing results (Johnson, 1992). Sampling of headwater catchments differs from lowland stream monitoring in that sampling tends to be closer to sediment sources and the hydrological regimes are more variable. These conditions require special consideration when developing a monitoring framework.

For this study, a method that could be programmed to trigger at various stream stages was required for sampling storm events at any time of the day or night. It was decided that a sampling strategy using a point measurement technique at a downstream location where the stream was well mixed would reduce spatial error. Rock and Taylor automatic pump samplers were located on Burnhope and Langtae Burns at the inlets to Burnhope Reservoir. These sites were considered suitable for monitoring suspended sediment concentration as they were accessible for repeated velocity readings, located at the inlets to Burnhope Reservoir and were in close proximity to brick pillars for securing the stilling wells. When selecting sampling frequencies for suspended sediment monitoring close attention was paid to Ferguson's (1987) general finding of a gradual increase in sediment yield underestimation with a decrease in sampling frequency. It was decided that samples would be taken at 6-hourly intervals continuously and an extra sampler would be initiated during storm events to monitor suspended sediment concentrations at 15-minute intervals. Each sampler had three trays of 16 bottles that required changing every 12 days for samples taken at 6 hourly intervals and with the onset of a storm, 12 hours of sampling at 15-minute intervals was possible. Once initiated it took approximately 2.5 minutes to pump 600 ml of stream water through plastic tubing from the inlet sited above the stream bed. The inlet tube was aligned upstream and anchored to a metal dexion rod fixed to a metal gate at the centre of the stream. After each sample collected a reverse pump action was activated to discharge any remaining water lying in the tubes. This procedure ensured that each point sample taken was representative of the suspended sediment concentration of the stream water at that point in time.

For storm monitoring at Burnhope, float switches were installed within the stilling well that triggered the samplers when activated. The height of the switch was varied after each event to enable a database of storm samples to be developed at a number of different flow stages.

4.2.2 Stream gauging stations

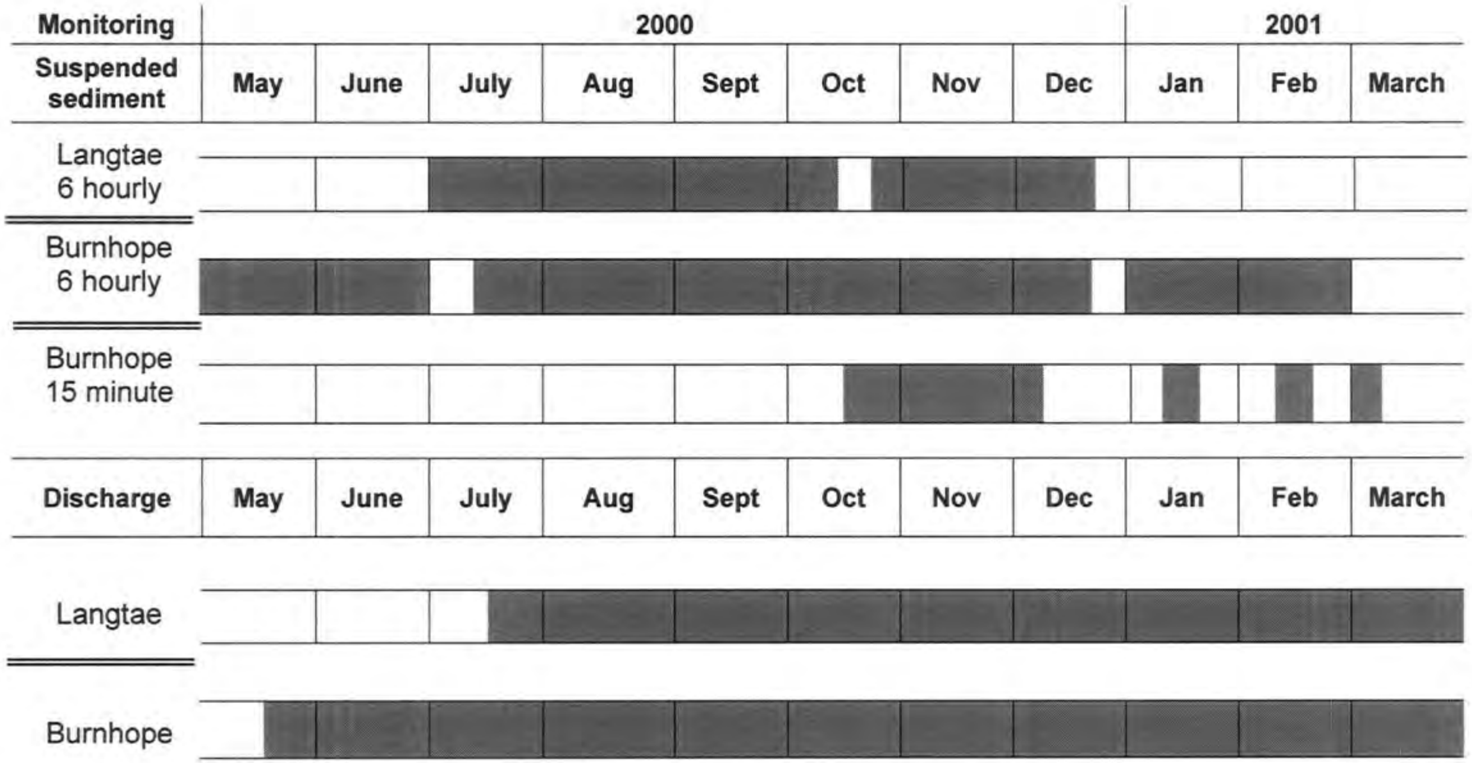
Two gauging stations were set up on Burnhope and Langtae Burn, one on each stream approximately 100 metres from the inlets to the reservoir. These site locations were chosen to ensure that the yields recorded represented inflows from both catchment areas. Each station consisted of a pressure transmitter housed in a stilling well linked to a datalogger and a Rock and Taylor pump sampler. Figure 4.2 is a photograph of the gauging site on Burnhope Burn taken during low flow. These gauging stations provided all data from which suspended sediment yields were estimated on both storm event and annual timescales. Figure 4.3 shows the time periods of monitoring suspended sediment and discharge on Burnhope and Langtae. Monitoring was brought to an abrupt end in March 2001 due to site closure caused by the Foot and Mouth outbreak. Unfortunately, this marked the end of any further fieldwork in the Burnhope and Langtae catchments until restrictions were lifted in the summer of 2002.

4.2.3 Discharge-velocity and stage measurements

Stage was recorded on Burnhope and Langtae Burns using pressure transmitters housed in stilling wells. At each site the pressure transmitter was linked to a data logger. The loggers were powered by a solar panel that trickle charged a lead acid battery. The purpose of the stilling well is to ensure accurate sensing of small changes in the water level and to exclude waves and turbulence from the main river flow (Shaw, 1996). The well was constructed from plastic piping (20 cm in diameter) with holes drilled along its length allowing for consistent water levels inside and out. Scale tape was attached along the side for ease in reading depth scales for converting stage to

Figure 4.2 Photograph of stream gauging station on Burnhope Burn taken during low flow. The stilling well is attached to the gatepost together with the white data logger box. The Rock and Taylor pump samplers are beneath the blue tarpaulin with plastic inlet piping feeding along the wall and into the stream.

Figure 4.3 Periods of suspended sediment and discharge monitoring on Burnhope and Langtae Burn from 2000 to 2001.



discharge. The well was secured to a stone pillar to protect it from being washed away during high flow.

In order to calculate discharge, velocity readings were required. Discharge (m^3 s^{-1}) was calculated using the velocity-area method that involves integration of depth and vertically averaged velocity measurements at successive locations across the stream cross-section (Dingman, 1994). This is a universally accepted method and 90% of the world's river discharges are calculated using this technique (Shaw, 1996). The velocity readings were taken using a velocity meter at 50 cm intervals along a fixed cross-section of the channel. Stream velocity profiles vary with stage due to changing friction from the channel bed and banks. To account for these discrepancies it was necessary to obtain mean velocity readings at as many different stages as possible. When taking velocity readings the probe was set at 0.6 of the water depth. There are systematic and logistical errors associated with these velocity readings. The instrumental error margin on the velocity meter is ±0.5%. During low flows the velocity can be difficult to measure due to ponding and eddy flows resulting in false consistent readings and negative values respectively, both are caused by boulders on the channel bed. During very high flows it is often dangerous to attempt wading into the channel. These errors can cause problems when measuring the extremes of the discharge record at both low and high flow.

4.2.4 Precipitation

The monitoring of precipitation at Burnhope is restricted to rainfall so the amount and frequency of snowfall has not been gauged at this site. Monitoring was carried out using a tipping bucket rain gauge levelled on a concrete flagstone. The gauge was connected to the datalogger at the Langtae gauging site and recorded total rainfall (mm) every 15-minutes. It is generally recognised that sites on flat land with few obstructions will yield the most representative data. It was therefore necessary to select a site that was not influenced by small-scale geographical or man-made features. There is a stonewall at the Burnhope site but the gauge was located more than ten times the height of the obstruction away to eliminate the rain shadow effect.

The level of the gauge was checked on a regular basis, as was the funnel of the rain gauge to ensure the pipe was free from obstruction from organic debris and algae. There are a number of errors inherent in rain gauge measurements. These included systematic errors from the instrumentation. Dingman (1994) reports how tipping bucket gauges often under-record during heavy rains and that temperature can interfere with their performance. To this end, instrumental errors have been estimated to account for 1-5% of the total catch (Winter, 1981). Another error could occur during periods of low-intensity rainfall, when there is insufficient rainfall to activate the tipping bucket. This type of rain would be sufficient to wet surface sediment and could play and important role in processes of sediment preparation but remains unrecorded in the rainfall record.

4.3 Mapping potential sediment sources and flood deposits

The location and morphology of stream-side scars, coarse-grained flood deposits and bedrock channel reaches in the Burnhope and Langtae catchments were mapped onto large-scale vertical aerial photographs (1:3300) taken in 1995. The mapping of potential sediment sources in the Langtae catchment was carried out in 2000 by Gifford (2000), while measurements for this project in the Burnhope catchment were delayed until summer 2002. Mapping and measuring techniques remain consistent between the two catchments to enable comparison of data.

The location of each stream-side scar and cut bank was marked onto the field photographs. The width and height of scar faces were recorded to assess the extent of exposed sediment at channel margins. The physical appearance of the sediment surface was noted, the degree of freshness (Warburton and Danks, 1998) and degree of vegetation coverage. In some cases the identification of discrete scars was problematic due to the continuum from scars into entrenched and high cut banks. Despite these issues, it is believed that the results represent the number, location and extent of stream-side scars in the Burnhope and Langtae catchments.

The location of each flood deposit and potential source was marked onto aerial photographs. The b-axis of the 25 largest clasts on each deposit was measured. Due to re-vegetation and deposit size, it was not always possible to measure 25 clasts on each deposit. For this reason, only the largest five clasts from each deposit were used in subsequent analysis.

4.3.1 Dating flood deposits using lichenometry

This section introduces the concepts behind dating of flood deposits using lichenometry and discusses the methods that have been employed in previous studies in upland fluvial systems. This background provides context for the methods adopted to date flood deposits in the Burnhope and Langtae catchments.

Lichenometry has been defined as the use of lichens to provide estimates of relative and absolute ages of the substrates on which they are found (Locke *et al.*, 1979). Lichens can be defined as fungus with one or more algae and / or cyanobacteria that live together forming a stable, identifiable body (Baron, 1999). The pioneering work of Beschel in the 1950s used lichens to measure the age of recent glacial moraines. Since this study, lichenometry has been used in a number of UK upland regions to date flood deposits (Milne, 1982; Macklin *et al.*, 1992b; Harvey *et al.*, 1984; Merrett and Macklin, 1999; Johnson and Warburton, 2002). A number of the most recent studies are listed in Table 4.1. Of the 35 plus species and subspecies that have been used in lichenometry, the most common is the crustose lichen named *Rhizocarpon geographicum*. The body (thallus) of this species varies in colour from yellow in bright light to green in the shade and has cracks (rimose) on the thallus surface which exposes the black underlying layer of fungal hyphae (Baron, 1999). The clearly defined, dark thalline margins of the *Rhizocarpon* genus, its longevity and relative abundance in upland regions makes it favourable in substrate dating (Locke *et al.*, 1979).

Lichenometry relies on the basic assumption that lichen thalli size is directly related to substrate age (Merrett and Macklin, 1999). A number of uncertainties surround this basic assumption and these include issues of lichen colonisation and local environmental conditions that could alter the consistency of growth rates within species. Most of these issues are addressed through well-constructed sampling strategies involving careful site selection and an understanding of lithology, climate and species abundance.

Other factors of importance when establishing a sampling strategy include species identification, sampling and measuring of lichens and the methods employed in determining absolute growth rates of thalli. Species identification is notoriously difficult and involves microscopy and more recently, analysis of the chemical compounds in lichens. On these grounds, it is doubtful whether reliable identification to species level is ever possible in the field (Innes, 1985a). Many workers have claimed to use the

Table 4.1 Table documenting past studies in upland catchments that have used lichenometry to date fluvial deposits.

Study area	Species	Measurement used	Method used to obtain rate	Growth rate (mm yr^{-1})	No of measurements on deposits	Source
Burnhope Burn, North Pennines	*Rhizocarpon* section *Rhizocarpon*	Max. axis of near circular thalli to nearest 1mm	Based on growth rate curve from Langtae Burn (Gifford, 2000)	0.39	Mean of five largest (if possible) thalli on each deposit	Present study
Langtae Burn, North Pennines	*Rhizocarpon* section *Rhizocarpon* *Lecanora*	Max. axis of near circular thalli to nearest 1mm	Linear regression	0.39 2.70	Mean of five largest (if possible) thalli on each deposit	Gifford (2000)
Raise Beck, Lake District	*Rhizocarpon* section Rhizocarpon	Max. axis of near circular thalli to nearest 1mm	Used curves of Macklin *et al.* (1992a), Merrett & Macklin (1999) & Lunan (1969)	0.29-0.4*	Mean of five largest (if possible) thalli on each deposit	Johnson and Warburton (2002)
Yorkshire Dales	*Rhizocarpon geographicum* agg. *Aspicilia calcarea*	Not given	Linear regression By correlation with *R. geographicum* curve	0.36 0.93	Mean of five largest thalli on deposit	Merrett and Macklin (1999)
Thinhope Burn, North Pennines	*Rhizocarpon geographicum* agg. *Huilia tubercolosa*	Longest axis to nearest 0.1mm	Regression Linear regression	0.39 0.82	Mean of three largest surface of known age	Macklin *et al.* (1992a)
Carlingill, Howgill Fells, Cumbria	*Rhizocarpon geographicum* agg.	Longest axis to nearest 0.1mm	Envelope curve	0.40	Largest thalli on each deposit	Harvey *et al.* (1984)
Harthope Burn, Northumberland	*Rhizocarpon geographicum* agg.	Min. axis to nearest 1mm	Extrapolation from one surface of known age	0.32	Mean of single largest thallus from each rock on deposit	Milne (1982a)
Crarea, Argyll, Scotland	*Rhizocarpon geographicum* agg.	Not given	Not given	0.50	Not given	Topham (1977)

* Growth rates dependent on substrate lithology

Table modified from Gifford (2000)

lichen species *Rhizocarpon geographicum* to date flood deposits (Table 4.1 - Harvey *et al.*, 1984; Macklin *et al.*, 1992a & b; Merrett & Macklin, 1999;) but on the basis of these difficulties it is unlikely that identification has been restricted to one species alone. To relieve confusion with respect to the *Rhizocarpon,* Innes (1985a) recommends classification of *Rhizocarpon* subgenus to the entire yellow-green subgenus and categorisation of *Rhizocarpon* section *geographicum* when identification has been made to the section level.

On the issues of sampling and measurement there have been a number of different methods used. Measurement of the 'largest inscribed circle' recommended by Locke *et al.* (1979) was rejected on the basis that multiple thalli could be recorded as single thalli and the use of near circular thalli only was seen to correct for this problem (Innes, 1985b). In terms of sampling, there has been much debate over the use of the largest lichen on a deposit versus the mean of a number of large lichens that has ranged from 3 to 10. Beschel (1961) implied that the largest thallus is the most representative of both the optimal micro-environment and the age of the substrate and Webber & Andrews (1973) concurred that any attempt to average the largest thalli is illogical (Locke *et al.*, 1979). Conversely, the mean of the five largest lichens can be seen as a useful assumption as the longer a substrate has been exposed, the greater the average age of lichens on a substrate will be (Matthews, 1973, 1974, 1975, 1977). There is also the issue that averaging a number of thalli sizes is more statistically significant than the single largest thallus (Matthews, 1974).

Absolute dating of substrates using lichenometry requires detailed knowledge of the rate of growth of the chosen lichen species in a possibly changing environment over an unknown length of time (Locke *et al.*, 1979). This can be achieved by direct or indirect method or, if possible, a combination of both. The direct method involves the measurement of the same lichen thallus at set intervals over time, while the indirect method uses lichen sizes on substrates of known age. The indirect method is the most common, usually involving the measurements of lichen thalli on gravestones, walls and other man-made substrates. There are several uncertainties with the indirect method, with size varying with not only age, but lithology, aspect and climate. It is therefore important to ensure uniform conditions by having the substrates of known age in close proximity of the study area. Age-versus-size relationships are determined using either linear regression (Macklin *et al.*, 1992b; Merrett & Macklin, 1999) or envelope curves (Harvey *et al.*, 1984) on graphs produced from lichen size on substrates of known age.

4.3.2 Method adopted for lichen measurement in the Burnhope and Langtae catchments

In the current study, flood deposits were analysed in both the Burnhope and Langtae systems. Lichens of the *Rhizocarpon* subgenus were identified in the Burnhope system and their distribution considered sufficiently ubiquitous for recording a range of flood deposits of different ages. For ease of description, the *Rhizocarpon* subgenus will be termed *Rhizocarpon* throughout the remainder of this study. In the Langtae system, three species were used to date flood deposits. These were from the *Lecidea* and *Lecanora* genera and from the *Rhizocarpon* section *Rhizocarpon* (Gifford, 2000). Due to uncertainty surrounding the exact identification of individual species, these lichens were referred to as *Lecidea*, *Lecanora* and *Rhizocarpon* respectively (Gifford, 2000).

The sampling strategy involved the examination and measurement of all near-circular thalli of the chosen genera on each deposit to the nearest 1 mm. The mean of the five largest thalli was then calculated to enable the relative sizes of lichens on deposits to be compared. The growth rates of the lichens were determined using the indirect method of absolute dating, using mean thalli sizes of the five largest *Rhizocarpon* recorded on gravestones in Burtreeford Bridge cemetery (NY 853403) (Gifford, 2000). This graveyard is approximately 4 km from the study site at 370 m O.D (Gifford, 2000). Linear regression was applied to the data to produce a size-versus-age curve for *Rhizocarpon* lichens. The growth rates determined from this regression were applied to the mean diameters of individual *Rhizocarpon* thalli on each deposit to determine absolute ages.

Gifford (2000) describes the detailed procedure for determining size-versus-age curves for *Lecidea* and *Lecanora*. It involved the use of flood deposits of known age in West Grain and Swinhope Burn both upper tributaries of the River Wear. West Grain is approximately 5 km south east of the study sites. Carling (1987a) described the depositional features consisting of debris flow lobes (NY 874371) and a boulder berm (NY 868368) formed in West Grain by a flash flood triggered by a thunderstorm on July 17th 1983. Gifford (2000) measured 100 *Lecanora* on the debris lobes and 50 on the boulder berm. In Swinhope Burn, 100 *Lecanora* and 100 *Lecidea* were measured on lateral bar features deposited during a flood in January 1995. Swinhope Burn (NY 896347) is located approximately 8 km south east of the study sites. As with the *Rhizocarpon* data, linear regression was used to determine growth rates for the

Lecanora and *Lecidea* lichens on growth curves and the dating of flood deposits can be found in Chapter 5.

4.4 Reservoir-based data collection

The reservoir-based data collection involved surveying of reservoir bed morphology, sampling of sub-aqueous sediments and monitoring of shoreline erosion. These procedures were carried out to evaluate the contemporary morphology of the reservoir bed and to investigate the spatial and temporal record of sediment accumulation within Burnhope Reservoir. Details of these techniques are provided in the following sections.

4.4.1 Bathymetric survey

A SonarLite portable single beam echo sounding system was used to perform a hydrographic survey of Burnhope Reservoir. The SonarLite sensor was attached to the front of an inflatable boat. A Magellan 10X Global Positioning System (GPS) was also mounted on the boat to enable the position of the boat to be fixed during the sonar survey. A base station was established on the shoreline. The GPS was run in differential mode to ensure sub-metre accuracy in position fixes. Thirty profiles were taken in a north to south and south to north direction and two long profiles running east to west from the input streams to the dam. Potential errors in the bathymetric measurements included variations in the level of the front of the boat due to weight distribution in the boat. These variations in weight distribution were kept at a minimum to reduce vertical distortions. The errors of using the Magellan GPS system in differential mode would give XY co-ordinates to an accuracy of approximately two metres and Z co-ordinates to an accuracy of approximately five metres. This is the maximum probable error but due to selective availability being set to zero, the survey of Burnhope is expected to be more accurate than these predictions. From examination of the data set from Burnhope Reservoir it was found that altitudes (reservoir level plus the height of the inflatable) remained consistent throughout the day. The data downloaded from the echo sounder were imported into Surfer 7 (a contouring and 3D surface mapping programme) to produce a map of the bathymetry of the reservoir bed.

The map was then imported into a GIS framework and the locations of the profiles determined from the GPS data.

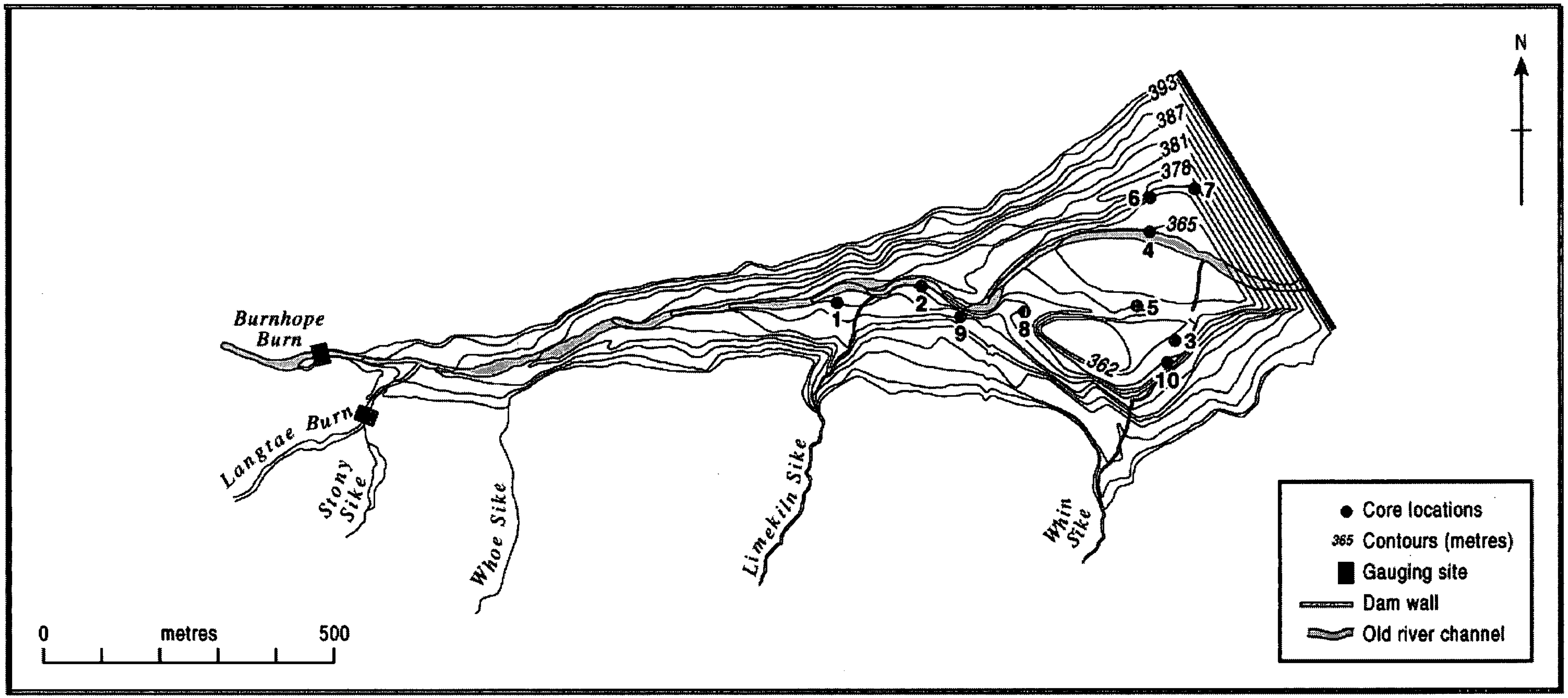
4.4.2 Reservoir sub-aqueous sediment sampling strategy and methodology

Ten cores of sediment were extracted from the reservoir bed using a Mackereth pneumatic corer in June 2000. This technique for sampling subaqueous sediment has been widely used in sedimentation studies (Mackereth, 1969; Foster and Charlesworth, 1994; White *et al.*, 1996b; David *et al.*, 1998). The main input streams to Burnhope Reservoir flow in from the west and outflow at the dam to the east. It was therefore assumed that the major variability in sedimentation would be along the length of the reservoir, west to east towards the dam wall. Figure 4.4 shows the bathymetry of Burnhope Reservoir digitised from 1935 construction plans together with core locations mapped using a Magellan hand-held differential GPS. Cores 1, 2, 5, 8 and 9 form a west-east transect while a number of cores (3, 4, 6, 7 and 10) were taken at various locations around the main transect in order to obtain a more comprehensive coverage. Coring was problematic towards the dam as the steep gradients on the north and south slopes of the reservoir restricted sediment sampling using the Mackereth coring equipment. Subsequent samples taken with a gravity corer confirmed minimal sediment deposition on steep slopes. Water depths restricted coring further to the east of core 1 but subsequent observations have shown little sedimentation in this narrower limb of the reservoir. Once transported to the laboratory the core samples were refrigerated at 2 °C before being sub-sampled at 1 cm intervals for analysis.

4.4.3 Monitoring shoreline erosion

There were ten sites selected to monitor reservoir shoreline erosion using erosion pins, six banks on the south and four banks on the north facing shoreline. The erosion pins were made from 2 mm diameter silicone bronze welding rods cut to lengths of 30-60 cm. Approximately 30 pins were inserted at each site in a network with ten profiles across and three pins down the bank face, one in the top, middle and lower sections of the bank. Measuring of pins was carried out using digital callipers and repeated three times for each pin. Monitoring was initiated on 11/10/00 with the intention of scheduling pin re-measurements on a two-monthly basis. Due to site closure during the Foot and Mouth outbreak, monitoring was restricted to the months December 2000 to January 2001.

Figure 4.4 Bathymetry of Burnhope Reservoir digitised from 1935 construction plans showing core locations and stream gauging sites on major tributaries of Burnhope and Langtae Burns.



4.4.4 Estimation of reservoir trap efficiency

The concept of reservoir trap efficiency and discussion on methods used to calculate trap efficiency for estimating sediment yields from sediments in storage has been outlined in Chapter 2, Section 2.5. There is a range of empirical curves available for estimating trap efficiency in reservoirs. From published studies, it appears that the choice of curve depends on the quality and quantity of data available. When estimating annual sediment deposition in Alpine Lakes in British Columbia, Evans (1997) adopted the simplest method proposed by Brune (1953) because of the lack of runoff and local precipitation data. As reservoir flow dynamics at Burnhope are limited, the trap efficiency curves of Brune (1953) have been used in this study. Trap efficiency estimates are also determined using the sediment balance equation based on quantification of the input, storage and output components of the reservoir sediment budget.

4.5 Laboratory methods

4.5.1 Filtering of water samples to determine suspended sediment concentrations

Water samples were collected as described in section 4.2.1 using Rock and Taylor pump samplers from the input streams of Langtae and Burnhope to determine catchment suspended sediment concentration over the study period. The samples were refrigerated and promptly filtered. The exact volume of sample in each 600 ml bottle was determined in a volumetric cylinder before being passed through pre-weighed Whatman GF/C 47 mm Glass Microfibre filter papers that retained particles down to 1.2 µm using a vacuum filter pump. The filter papers were oven dried overnight and placed in a desiccator to cool. Once cooled the papers were re-weighed to determine the mass of residue sediment. Using the mass of sediment and the volume of the sample, suspended sediment concentrations (SSC) in milligrams per litre (mg l^{-1}) were calculated.

$$SSC = [(M_{fs} - M_f) / V_{ws}] * 1000000 \qquad \text{(Equation 4.1)}$$

where

M_{fs} = mass of dried filter paper and sediment (g)

M_f = mass of clean filter paper (g)

V_{ws} = volume of water sample filtered (ml)

4.6 Sediment characterisation for core description and sediment yield calculation

4.6.1 Core description and chronology

Before sub-sampling, stratigraphic and lithological analysis on each core was carried out. Lithological analysis was conducted recording colour and texture of the sediments. Stratigraphic descriptions were made for each core before the sediments were carefully extruded to minimise compaction. Core stratigraphy was generally homogeneous with undefined contacts. Colour and texture were the most useful characteristics for describing these sediments and this was noted when each core was extruded and sub-sampled at 1 cm intervals. These samples were packed into petri dishes, sealed and refrigerated. On each sub-sample a series of physical (dry bulk density (DBD), loss on ignition (LOI), particle size analysis) magnetic (magnetic susceptibility) and radiometric measurements (^{137}Cs dating) have been carried out providing data for core correlation and chronology. Table 4.2 summarises the physical techniques carried out on sub-samples of each of the 10 cores and identifies the three cores that were dated using ^{137}Cs. Further description of analytical techniques is provided in sections 4.6.2 to 4.7 while detailed stratigraphic descriptions of cores 1, 6 and 8 are presented in Chapter 7.

4.6.2 Dry Bulk Density

In order to account for spatial variability, density measurements were made on every core retrieved from Burnhope Reservoir. Dry bulk density was determined for each sample using a modified volumetric syringe (60 ml) and the dry sample weight. The top section of the syringe, where needles are usually attached was removed leaving a cylindrical tube with a sharpened edge and plunger. A sample was taken by pressing the sharp end of the syringe into each 1 cm slice of core sediment to obtain consistent volumes from each core sample. These samples were then oven dried at 100 °C for 12 hours, cooled, re-weighed at 25 °C and dry bulk density (DBD %) calculated using the following equation;

Table 4.2 List of the physical and radiometric analyses used on core sediments.

Core	Depth	^{137}Cs	LOI	Particle size	Dry bulk density	Magnetic susceptibility
1	0.76	X	X	X	X	X
2	0.08		X	X	X	
3	0.57		X	X	X	
4	0.10		X	X	X	
5	0.73		X	X	X	X
6	0.51		X	X	X	
7	0.13		X	X	X	
8	0.95	X	X	X	X	X
9	0.93	X	X	X	X	
10	0.12		X	X	X	

$DBD = (M_o - M_c) / V_s$ (Equation 4.2)

where

M_c = mass of crucible (g)

M_o = mass of cooled crucible and sample post oven (g)

V_s = sample volume (cm^3)

The inherent moisture content of the sediments was also determined from this oven drying process using the equation below.

Inherent moisture (%) = $[((M_s - (M_o - M_c)) / M_s] * 100$ (Equation 4.3)

where

M_s = sample mass (g)

M_w = mass of dried crucible and sample pre oven (g)

4.6.3 Loss on ignition

Loss on ignition (LOI) is a common and widely used technique for determining organic content of reservoir and lake sediments e.g. (Labadz, 1988; Evans, 2000), and is a useful tool for correlating different sediment cores with distinct LOI signatures (Heiri, 2001). To determine the organic content of each 1 cm sample of core, approximately 7 g of oven-dried sediment was disaggreated using a pestle and mortar. This sediment was weighed in a dried crucible and placed in a Carbolite ashing muffle furnace (OAF 11/1) furnace at 550 °C for four hours. Once cooled in a dessicator, the crucible and sediment were re-weighed and the amount of organic matter present determined by using the following equation

LOI (%) = $[(M_o - M_f) / (M_o - M_c)] * 100$ (Equation 4.4)

where

M_f = Mass of cooled crucible and sample post furnace (g)

The furnace exposure time and sample size remained consistent throughout the analysis to minimise errors between sample runs (Heiri, 2001).

4.6.4 Particle size analysis

Approximately 0.3g of air-dried sediment from each 1 cm core sample was treated with 20% hydrogen peroxide and distilled water and placed in a water bath for two hours to remove organics. The samples were then centrifuged at 4000 rpm for four minutes and the supernatant water decanted. Distilled water and 2 ml of Sodium hexametaphosphate solution were added to reduce sediment flocculation. The samples were analysed using a Coulter laser granulometer LS230 particle size analyser that measured particles of the size range 0.1-2000 μm. This granulometer had a polarisation intensity defraction scattering (PIDS) facility for measuring particles between 0.1–0.04 μm increasing the measurement range of particles to between 0.04-2000 μm. Recommended obscuration values of 12-15 % were maintained throughout analysis measuring particles between 0.04-2000 μm. Two runs were carried out for each sample and an average taken. If the runs produced visibly different particle size distributions, the samples were rerun. The results were split into sand, silt and clay fractions in accordance with British Standards.

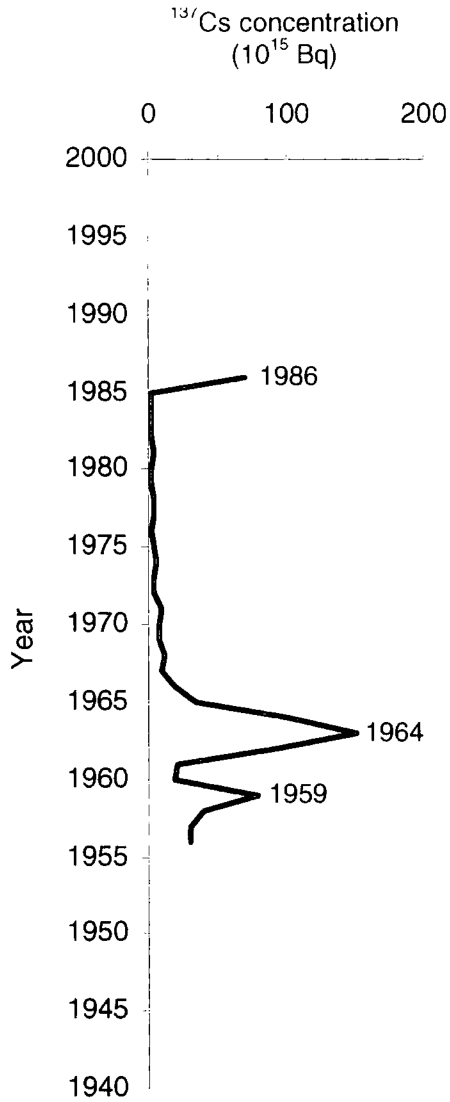
4.6.5 Magnetic susceptibility

Detailed magnetic susceptibility measurements were carried out on air-dried, disaggregated sediment packed into 10 ml plastic pots. The magnetic susceptibility was measured using a Bartington MS2B single sample, dual frequency susceptibility meter. The samples were measured at both low and high frequency (0.46 and 4.6 kHz) to detect the presence of any ultra-fine magnetic grains. These magnetic measurements were carried out on three cores 1, 5 and 8 (Table 4.2).

4.7 Establishing ^{137}Cs concentrations in core sediments

The sources of ^{137}Cs in the environment, adsorption of ^{137}Cs by soils and sediments and the application of the ^{137}Cs approach to assessing sediment erosion and deposition has been discussed in Chapter 2, Section 2.6. Determining the concentration of ^{137}Cs in sediment layers using gamma ray detection can be used to date sediment in storage. Profiles of ^{137}Cs concentrations are determined and the peaks in ^{137}Cs concentration attributed to periods of enhanced atmospheric ^{137}Cs concentrations in 1959, 1963 and 1986. Figure 4.5 shows the profile of ^{137}Cs fallout

Figure 4.5 Profile of ^{137}Cs fallout over the Northern Hemisphere produced from data from Cambray *et al.* (1987).



recorded over the Northern Hemisphere reported by Cambray *et al.* (1987) and highlights these peaks in atmospheric ^{137}Cs concentrations in 1959, 1963 and 1986.

The following section provides a brief introduction to environmental radioactivity and gamma ray detection with respect to measuring ^{137}Cs levels in sediments. A more detailed account of the background to environmental radioactivity can be found in and Kathren (1984) and Eisenbud (1987) while Higgitt (1990) and Walling and Collins (2000) provide a comprehensive account of gamma ray detection, detector calibration and data acquisition.

4.7.1 Environmental Radioactivity

The sources of radiation on the earth's surface are both natural and artificial. Some naturally occurring radiation exists in the form of cosmic rays of extraterrestrial origin, but the majority found on earth is from internal or terrestrial sources (Kathren, 1984). Artificial radiation originates from fission reactions in power generation industries and nuclear weapons testing by the military. Fission is the name given to the breakdown of a nucleus into a neutron and two daughter nuclei.

Radiation is emitted when the nucleus of an unstable nuclide undergoes atomic transformation. There are three types of radioactivity, alpha, beta and gamma radiation. Alpha radioactivity relates to the emission of particles in the form of helium nuclei while beta radioactivity corresponds to the transformation, in the nucleus, of either a neutron into a proton or of an electron. Gamma radioactivity, unlike the other two, is not related to a transmutation of the nucleus. It results from the emission of electromagnetic energy in the form of protons either from the nucleus as gamma rays or from orbital electrons as X-rays.

When one nucleus is transformed into another by radioactive fission it is said to disintegrate or decay. The activity of a radioactive body is the number of disintegrations of its atoms in one second. It is measured in becquerels and one becquerel (Bq) corresponds to the disintegration of one atomic nucleus per second. A variety of different nuclides are produced by fission reactions, these are termed daughter nuclides of which some are relatively short-lived. During the decay of a nucleus, the transformation of energy is not always instantaneous. This can lead to the formation of a short-lived nuclide that is termed an isomer. This is the case for the beta decay of ^{137}Cs that produces an excited daughter isomer of Barium (^{137m}Ba), which in turn emits a gamma ray. The unit of electromagnetic energy possessed by gamma rays is measured by the electron volt (eV) (Higgitt, 1990). Gamma rays have narrow energy ranges at keV levels and in the case of ^{137}Cs the gamma ray emitted by the daughter isomer ^{137m}Ba has an energy level of 661.6keV (Higgitt, 1990). The activity of ^{137}Cs is determined by counting the number of gamma ray emissions at this energy level.

4.7.2 Gamma ray detection

The gamma rays emitted from a sediment sample were recorded using an EG&G Ortec hyper-pure germanium well detector coupled to a 4096 multi-channel analyser (MCA). The levels of ^{137}Cs are measured within the detector by counting the number of gamma rays emitted by the daughter isomer ^{137m}Ba. The detector is capable of measuring emissions between 0 and 800 keV, but in this project only gamma rays of ^{137}Cs at 661.6 keV were relevant. These emissions are recorded and converted to a relative voltage pulse and identified by the multi-channel analyser to produce photopeaks (Higgitt, 1990). The area of activity around this energy level has been determined as a region of interest (ROI) and is measured to determine the gross area of the photopeak, which equals the total number of ^{137}Cs counts. The three channels either side of the ROI spectrum are used to determine the background radiation. The amount of counting time required to measure the activity of a sample is dependent on the sample size and detector efficiency (Walling & Collins, 2000). The samples taken from Burnhope Reservoir were measured for 48 hours based on detector efficiency of 0.0685.

The information provided by the above analysis can then be used to calculate the ^{137}Cs content of the sample. The ^{137}Cs activity is the concentration of ^{137}Cs per unit mass (Bq kg^{-1})

$$SSA = (AP \times 100000) / (T \times M \times DE) \qquad \text{(Equation 4.5)}$$

SSA = sub-sample activity (Bq kg^{-1})
AP = peak area
T = time
M = sample mass (kg)
DE = detector efficiency for sample container (Walling and Collins, 2000)

4.7.3 Accounting for potential error in results

As the estimation of ^{137}Cs is based upon the area of activity of the 661.6 keV peak in the spectrum, the degree of analytical precision is concerned with the size of this peak (Walling & Collins, 2000). The algorithm for determining the percentage error of the peak area (*PE*) is as shown

$$PE = \left(\frac{\sqrt{AP}}{AP} \right) K \qquad \text{(Equation 4.6)}$$

AP = area of peak

K = constant (1.96 at 95% confidence level)

The calculations of ^{137}Cs activity in sediments are expressed in terms of associated percentage error that is often quoted as ± 1 standard deviation either side of the mean. Throughout this thesis, ^{137}Cs measurements of individual samples are reported as the activity ± net area standard error.

4.7.4 Detector calibration

The detector was calibrated against certified samples of known activity. The procedure uses an environmental sample of Baltic Sea sediments supplied by IAEA. The calibration sediment has been measured in a variety of different sample geometries to establish measuring efficiencies for different sample sizes and configuration. The detector was calibrated using the following formula:

$$f(M_o) = \left(\frac{C_o}{T_o} - \frac{C_b}{T_b} \right) \times 100000 \times \left(\frac{1}{M_o (A_o e^{-\lambda(t-t_o)}} \right) \qquad \text{(Equation 4.7)}$$

where

f = detector efficiency for mass (M_o) (g)

C_o = total counts

T_o = count time (s)

C_b = background counts of sample of same weight and zero ^{137}Cs content

λ = decay constant

t = present date (yr)

t_o = date of sample collection

A_o = sample activity (Bq kg^{-1})

The sediment samples from Burnhope Reservoir were analysed once calibration was completed. Approximately 3 g of sediment from each 1 cm sample taken from reservoir cores were oven dried at a low temperature (40°C) for 72 hours then disaggregated using a pestle and mortar. The samples were sieved and the fine fraction (< 2 mm) packed into specially fabricated plastic sample holders designed to fit inside the well recess of the detector. Each sample was placed in the well detector for 48 hours to obtain the most representative count.

4.8 Chapter summary

This chapter has outlined the methods of field based data collection and discussed the suite of laboratory techniques employed to investigate sediment delivery in the Burnhope and Langtae catchments. Stream gauging stations were set up on Burnhope and Langtae Burn and each station consisted of a pressure transmitter, datalogger and automatic pump sampler. Suspended sediment concentration was monitored at six hourly intervals for a ten-month period at the Burnhope and for eight months at the Langtae site. This was supplemented by storm sampling at 15-minute intervals at the Burnhope site. Stage was monitored at 15-minute intervals for the duration of the suspended sediment concentration-monitoring period and this record converted to discharge using stage-velocity measurements. Precipitation monitoring was restricted to rainfall and was recorded at 15-minute intervals for 10 months.

Potential sediment sources and flood deposits were identified using a rapid assessment mapping approach in both catchments. Enlarged aerial photographs provided the base map for locating the sources and stores of sediment in the field and lichenometry was used to provide relative dates for flood deposits. Lichens of the *Rhizocarpon* subgenus were measured in the Burnhope system while lichens from the *Lecidea* and *Lecanora* genera were also measured in addition to those of the *Rhizocarpon* subgenus in the Langtae system. Absolute dates of the substrates were estimated using the indirect method of measuring lichen sizes on substrates of known age, in this case gravestones.

The reservoir-based data collection involved surveying of the morphology of the reservoir bed to produce a bathymetric survey of present sediment depths, monitoring shoreline erosion and sampling of sub-aqueous sediments. Shoreline erosion was monitored at ten sites around the reservoir for a two-month period November 2000 to January 2001. The aim of this monitoring was to provide estimates of the input of sediments from bank erosion around the reservoir as a component of the sediment budget. Ten cores of reservoir sediment were retrieved along a transect from the proximal to the distal limb of the reservoir. The sediments were transported to the laboratory and sub-sectioned into 1 cm samples and the characteristics of the sediment were determined using a series of physical and radiometric techniques. The particle size, organic content, magnetic susceptibility and dry bulk density of the sediment samples were determined using a laser granulometer, ashing furnace, a magnetic susceptibility meter and a modified volumetric syringe respectively. Gamma ray detection was carried out on the sediments from cores 1, 8 and 9 using an Ortec hyper-pure germanium well detector. The background to environmental radioactivity, gamma ray detection and detector calibration has been outlined. Table 4.2 provided an overview of the physical and radiometric techniques applied to the sediments of each core. Figure 4.1 outlined the data collection strategy from the catchment and the reservoir used to investigate the sediment delivery system using a sediment budget framework. Overall, this chapter provided a detailed review of the methods of data collection and laboratory analysis used and forms a basis from which the results chapters now stem.

CHAPTER 5 - CATCHMENT BASED ASSESSMENT OF THE BURNHOPE AND LANGTAE SEDIMENT SYSTEMS

5.1 Introduction

A theme central to fluvial geomorphology is the spatial and temporal pattern of sediment transfer in drainage basins (Macklin and Lewin, 1989). Understanding sediment transfer involves identification of contemporary sediment source and storage zones and evaluation of the processes linking these zones. The dominant controls on the processes of sediment supply and transfer are dependent on the timescale of interest. Climate and geology control channel morphology over the longest timescales (geologic time) while channel morphology influences flow and sediment supply over more recent timescales (Schumn and Litchy, 1965). Previous research into sediment delivery in upland catchments of the UK has concentrated on the influence of sediment supply on channel morphology (Harvey, 1977, 1991; Macklin and Lewin, 1989; Johnson and Warburton, 2002;). This has included investigation into timescales of hillslope/channel coupling (Harvey, 1994, 2001, 2002; Warburton and Higgitt, 1998) and the geomorphic impact of flood events on upland fluvial systems in England (Carling, 1986a & b; Macklin *et al.*, 1992a & b; Merrett and Macklin, 1999), Wales (Newson, 1980a) and Scotland (McEwen, 1987, 1989a & b, 1990). Debate into the likely response of sediment delivery systems to climate change is of particular interest in contemporary studies as the magnitude and frequency of flooding is a key element in managing sediment erosion and deposition in populated lowland regions (DOE, 1995). The amount and calibre of sediment from headwater catchments controls the channel morphology downstream (Harvey, 1991) and therefore research into sediment delivery systems in headwater catchments in terms of past, present and future scenarios is key in understanding the impact of climate change in many drainage basins.

This study is concerned with sediment transfer at the catchment scale providing a spatial framework for understanding sediment delivery in the Burnhope and Langtae catchments by characterising the extent of contemporary sediment sources, defining the degree of slope/channel coupling and identifying the main storage zones. A geomorphological map of the catchments is used to determine sediment source and storage zones and highlight features of significance in terms of sediment delivery. A sub-system sediment budget has been developed to evaluate coarse and fine-grained sediment transfer between these source and storage zones. Lichenometry is used to establish a chronology of coarse sediment transport in both catchments, which is then compared to daily rainfall totals from local and regional records. The results from this chapter are based on data from a variety of sources. Aerial photographs and Ordnance Survey maps provide the basis for catchment mapping while ground-based photographs provide examples of features observed in the field. The results presented from the Langtae catchment are based on Gifford (2000) and these together with data from the Burnhope catchment form an assessment of the sediment delivery potential in the catchments feeding Burnhope Reservoir.

5.2 Mapping of sediment delivery components in Burnhope and Langtae catchments

A geomorphological map of Burnhope Burn and Langtae Burn is presented in Figure 5.1 (Enclosure 1 – at back of thesis). This map was created based on field mapping of sediment sources and channel features onto 1:3300 aerial photographs taken in 1995. The map shows the features of importance in-channel sediment transfer: the channel margins, location of incised sections, stream-side scars, flood deposits and also features of channel morphology including bedrock reaches, step-pool sections and areas of disturbance from mining and channel engineering. Figure labels on the map correspond to photographs included in the text, providing the reader with a spatial representation of the locations of features of interest and variations in channel morphology. The boxes on the map represent reaches of the channel that are referenced and discussed in the text.

Table 5.1 provides a summary of stream characteristics in the Burnhope and Langtae systems and reveals that 59 and 48% of the total stream length were mapped in the Burnhope and Langtae catchments, respectively. Of the remaining streams, 28 and 23% were ephemeral channels in the Burnhope and Langtae systems, respectively and were therefore not considered in the classification of stream order. Field observation revealed that the unmapped channels were small and contained few potential sources, therefore mapping was concentrated in the larger tributaries. Along the 10.25 km of mapped stream in the Burnhope system 136 separate flood deposits, 77 valley-side scars and 29 cut banks were identified. On Langtae Burn 103 flood deposits, 76 valley-side scars and 54 cut banks have been mapped. The upper reaches of both the Langtae and Burnhope systems are confined by bedrock. Average stream slope is greatest in the first order tributaries with those in the smaller Langtae system recording

Table 5.1 Characteristics of streams in the Burnhope and Langtae systems.

	Burnhope catchment			Langtae catchment		
	Burnhope main	Sally Grain	Scraith Burn	Langtae main	East Langtae	West Langtae
Stream order	2nd	1st	1st	2nd	1st	1st
Stream length (km)	2.49	4.10	3.66	1.87	1.42	1.47
Average stream slope (m/m)	0.023	0.058	0.054	0.075	0.085	0.076
Total mapped stream length (km)		10.25			4.76	
Total unmapped stream length (km)		5.20			3.97	
Ephemeral stream length (km)		2.03			1.21	

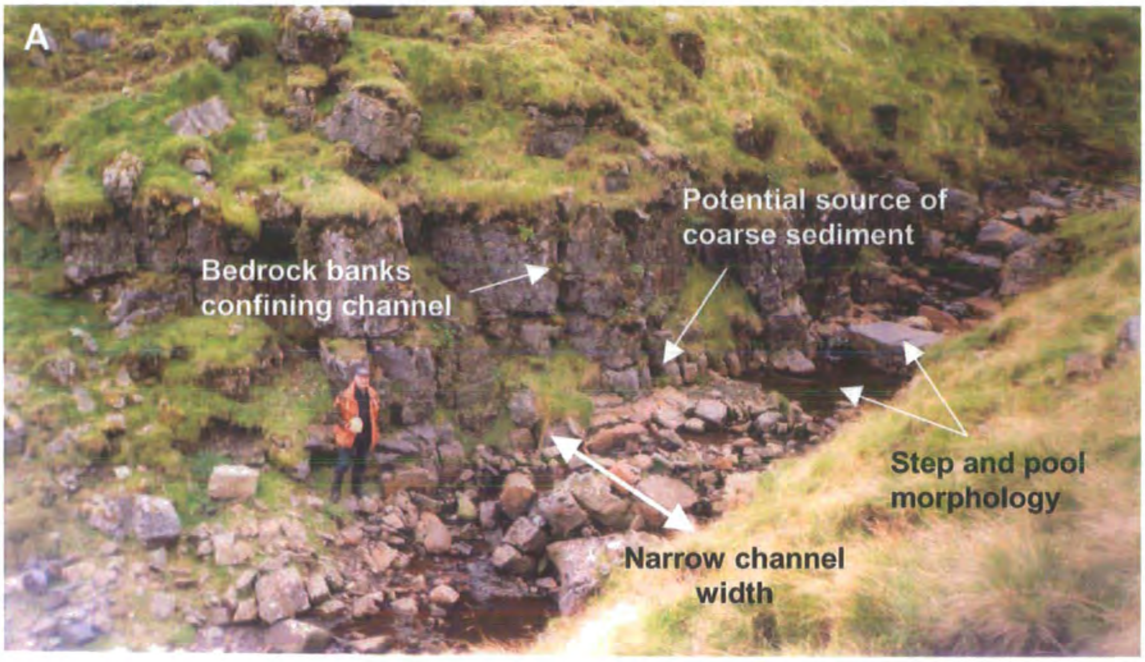
overall greater average stream slopes. Gifford (2000) reported a positive linear relationship between approximate valley-floor width and distance downstream in the Langtae channel. This is typical of headwater streams in upland catchments (Milne, 1983). Figure 5.2 A and B are photographs showing degrees of confinement of the channel from the headwater reaches of Scraith Burn to the lower reaches of Burnhope Burn at the inlet to Burnhope Reservoir. The degree of confinement has implications for sediment supply and transfer. The upper reaches of Scraith Burn have steep sections where bedrock slopes supply coarse sediment directly to the stream system resulting in step-pool morphology. The gentle unconfined interfluves of the lower reaches of Burnhope Burn show evidence of sediment storage both on floodplains and within the channel margins as bars. Despite there being evidence of channel engineering in these lower reaches of Burnhope Burn, the morphology and gradient of the channel lends itself to transfer, deposition, storage and reworking and contains a series of active, semi-active and dormant sediment stores.

Many reaches in the upper tributary streams have bedrock beds, an example of which is shown in Figure 5.3. As a result, sediment storage within these reaches is restricted to coarse-grained deposits with little storage along the channel bed (Figure 5.2 A). In the lower reaches gravel and boulder bars are located in the active channel (Figure 5.2 B) and old deposits are evident as terrace fragments at various heights above the present channel in various stages of re-vegetation. These sediments are moved primarily by flood events as a result of the flashy nature of the system. The location and extent of these deposits are identified in Figure 5.1.

5.3 Potential sources of sediment

Based on field observations and air photograph analysis, potential sediment sources in the Burnhope and Langtae stream systems are defined as bare areas of sediment directly coupled to the channel or sources located within the channel margins. The majority of land surfaces in these catchments are covered by vegetation and only where bare surfaces are connected to the channel system will sediment be delivered via surface wash processes. Features such as stream-side scars and cut banks are the main sources of minerogenic sediment. Figure 5.4 is a sub-system sediment budget developed based on observation of dominant sources of sediment to the system. Cut banks and stream-side scars provide a source of both coarse and fine-grained sediment. Direct coupling between these sediment sources and the channel will occur when flow exceeds base-flow conditions. Both coarse and fine-grained

Figure 5.2 Variations in the degree of channel confinement in (A) the steep headwater reaches of Scraith Burn and (B) lower reaches of Burnhope Burn.



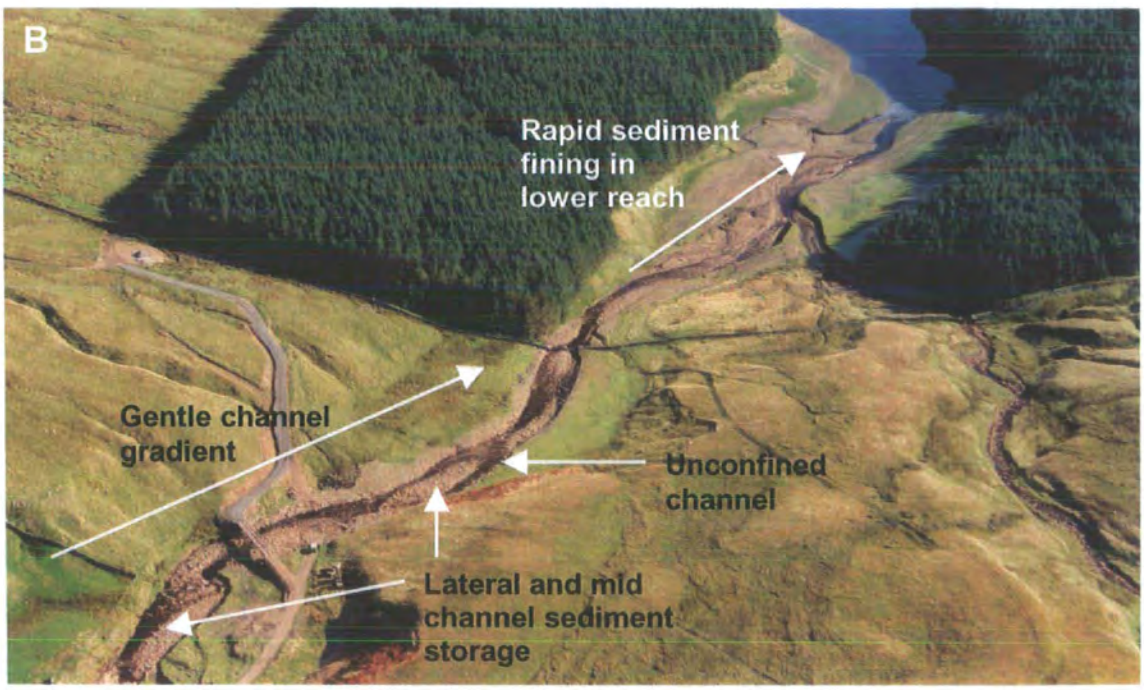
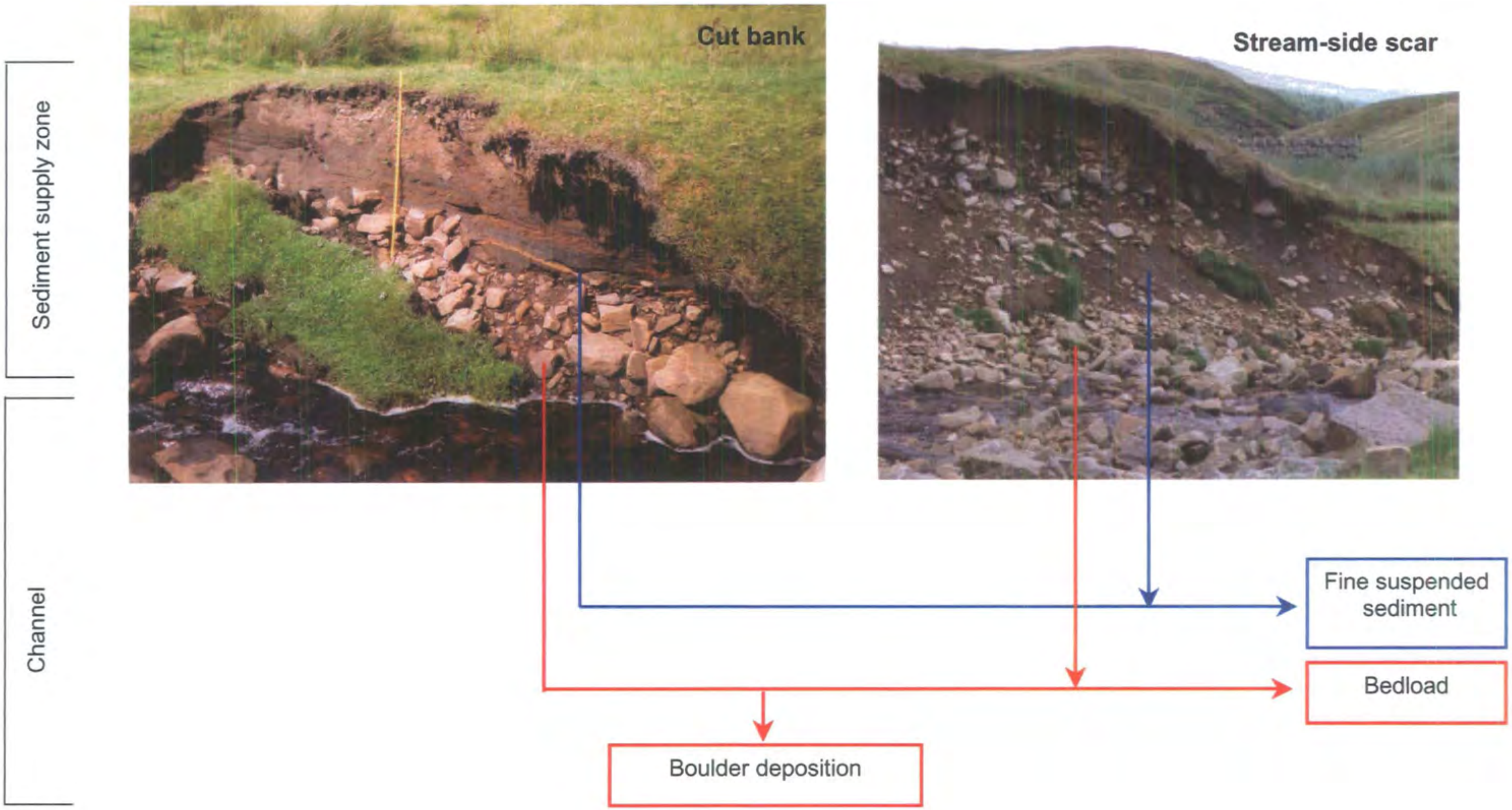


Figure 5.3 A bedrock channel reach in Scraith Burn.

Figure 5.4 A local sediment budget showing the supply of fines, gravels and boulders to the channel from cut banks and stream-side scars in the Burnhope system.



sediments are produced from eroding Devensian glacial tills and solifluction material. There is evidence of failures occurring in vegetated bank sediments along the channel margins (Figure 5.4). The sources provide periodic slumps of sediment into the active channel and occur at sites of active bank erosion. Incised gully systems form potential sources of organic (peat) sediments in the upper reaches of the tributary streams of Sally Grain and Scraith Burn in the Burnhope system and East and West Lang Tae in the Langtae system as shown on Figure 5.1. Table 5.2 is a summary table showing the number of stream-side scars and cut banks in the Langtae and Burnhope systems together with mean lengths of the features in the Burnhope system. The data on lengths of cut banks and stream-side scars are not available for the Langate system. There are more features occurring in the second-order stream systems than in the first. This is related to longer stream lengths in the second order channels and a greater degree of connectivity between hillslope and channel.

5.3.1 Stream-side scars

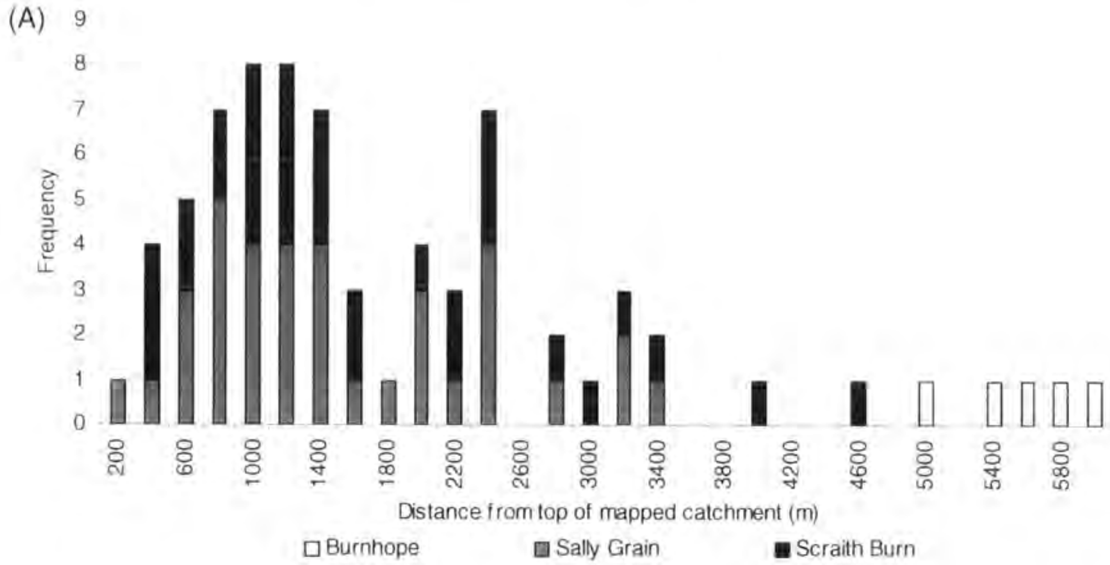
Stream-side scars form at locations along the channel network where the stream impinges on valley sides. Figure 5.5 A shows the frequency of stream-side scars in the Burnhope system graphed by distance downstream at 200 m intervals. There are approximately equal numbers of scars located on Sally Grain and Scraith Burn. This accounts for 94% of scars in the system located in second order tributaries, with only 6% of scars located in the upper reaches of Burnhope Burn. Figure 5.5 B shows that the distribution of stream-side scars in the Langtae system follows a similar overall trend with 65% of scars located in the first order tributaries of West and East Lang Tae. A larger percentage (35%) of scars were recorded in Langtae Burn in comparison to Burnhope Burn which are both second order streams. Figure 5.6 shows cumulative frequency of stream-side scars in both catchments against distance downstream. The frequency of occurrence of stream-side scars is greater in the smaller Langtae system with 22.4 scars km^{-1} of channel in comparison to 12.8 scars km^{-1} of channel in the Burnhope system. In the Langtae system 75% of scars are located in the top 50% of the catchment. Approximately 80% of scars are located in the upper 50% of the Burnhope catchment where the channel is steep and laterally confined by bedrock with an altitude range of 240 m. The lower half of the catchment that has 16% of scars and a smaller altitude range of 80 m.

There is a peak in the number of scars around 2400 m from the top of the mapped catchment in both Sally Grain and Scraith Burn (Figure 5.5 A). These scars are

Table 5.2 Summary table showing the number of stream-side scars and cut banks in the Langtae and Burnhope systems with mean lengths of features in the Burnhope system.

	Catchment system	1st order stream	2nd order streams	Total system
Number of scars	Langtae	48	28	76
	Burnhope	73	4	77
Mean scar length (m)	Burnhope	14.3	19	14.6
Number of cut banks	Langtae	29	25	54
	Burnhope	26	3	29
Mean cut bank length (m)	Burnhope	29.7	51.1	31.9

Figure 5.5 Frequency distribution of stream-side scars in the (A) Burnhope and (B) Langtae systems. Scars grouped at 200 m intervals.



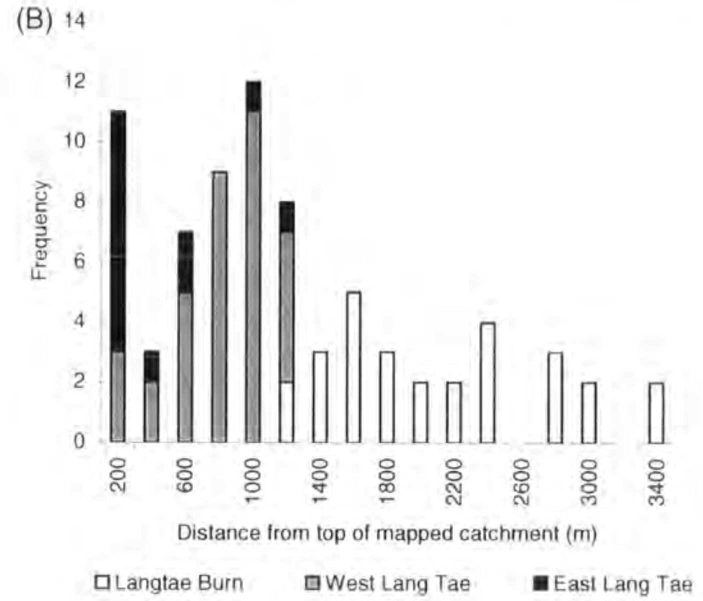
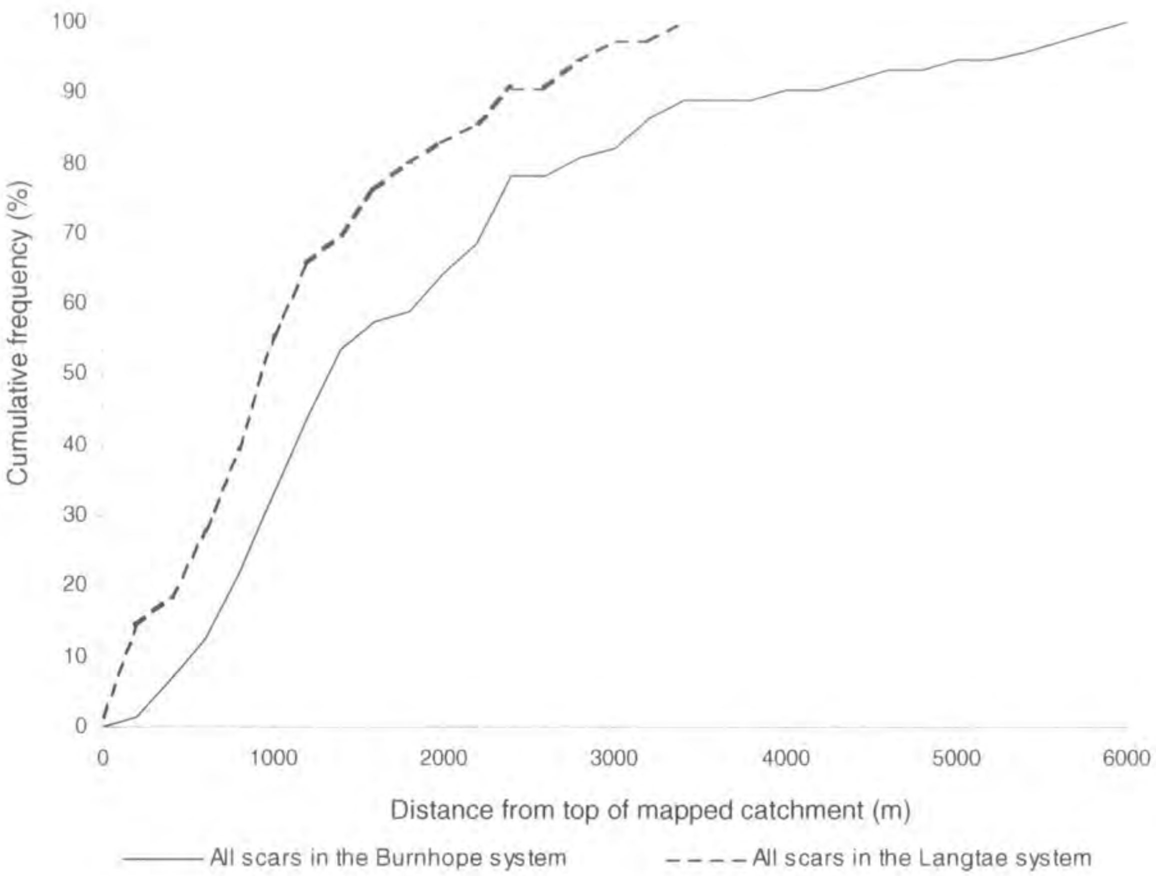


Figure 5.6 Cumulative frequency of all stream-side scars in the Burnhope and Langtae catchments against distance downstream.



located directly downstream of hushes that form part of the mining legacy in these channels. It is likely that disturbance from hydraulic flushing of sediment has supplied considerable volumes of coarse-grained sediment to the channel resulting in instability immediately downstream of the hushes. Figure 5.7 (Figure 5.1) is a photograph of the hush on Scraith Burn that is now totally re-vegetated. There is evidence that this feature may have been a potential local source of coarse sediment during the mining period. Boulder deposits at the toe of the hush are a mixture of mining material and flood deposits that block the mouth of the hush.

Assessing the frequency of stream-side scars in the Burnhope and Langtae systems alone is a poor measure of evaluating the sediment supply system. The surface area of exposed sediment and the degree of coupling between the scar and the channel are important parameters for assessing sediment supply from identified sources to the system. Table 5.3 provides a summary of scar surface area in both systems. Figure 5.8 shows the surface area of stream-side scars in relation to distance from the top of the mapped catchment for the Burnhope and Langtae catchments respectively. The filled symbols represent scars likely to be coupled to the stream, while the unfilled symbols represent uncoupled scars. In the Burnhope catchment the majority of scars have surface areas of less than 200 m^2. Of the nine scars with surface areas between 200 and 550 m^2 67% are located in the top 1000 m of the catchment where the stream system is highly confined by bedrock. One scar in the lower reaches of Burnhope Burn has a surface area of 513 m^2 and is the second largest in the catchment. Figure 5.9 (Figure 5.1) shows this scar and highlights the extent of exposed fine sediment, which is eroding and clearly demonstrates scar to channel coupling. Boulder deposits at the toe of the scar armour the active slope at low flow, but the scar is coupled during moderate flow. This scar is a site of slow mass movement and there is evidence of rill erosion on the active surface of the scar, which testifies to a potentially significant local source of fine sediment during high intensity rainfall events.

Figure 5.8 (B) presents scar surface area data for the Langtae system. Figure 5.10 is a cumulative frequency plot of surface area of individual scars in the Burnhope and Langtae systems. The surface area of individual scar faces is smaller in the Langtae catchment (Table 5.3) with 98% of scars with surface areas of 150 m^2 or less (Figure 5.10). The largest scar in this system is located on Langtae Burn towards the lower reaches of the channel. Gifford (2000) notes that the scar surface is poorly sorted and solifluction deposits are evident. Half of the basal length of the scar is coupled to the channel with the remainder protected by a boulder toe and therefore likely to deliver little sediment during low to moderate flow.

Table 5.3 Stream-side scar surface area in the Langtae and Burnhope systems.

	Catchment system	1st order stream	2nd order streams	Total surface area (m^2)	% of scars coupled to channel
Scar surface area (m^2)	Langtae	1265	1735	3000	78
	Burnhope	5261	784	6045	75

Figure 5.7 Re-vegetated hush on Scraith Burn showing evidence of historical sediment supply relating to mining activity in the Burnhope system.

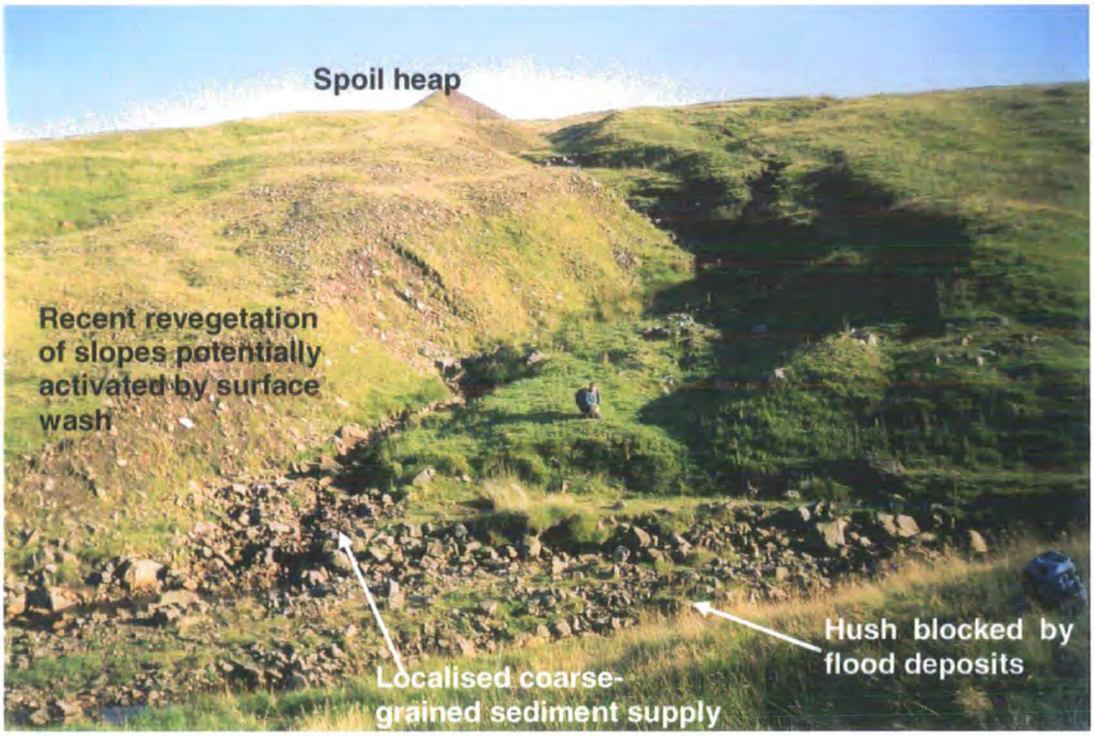
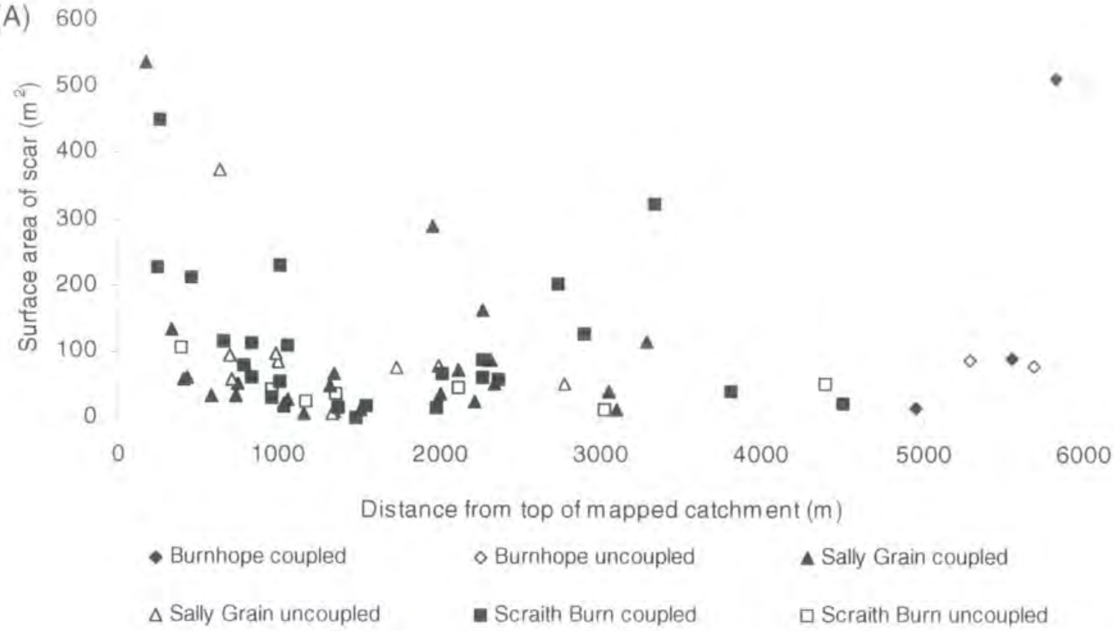


Figure 5.8 Surface area of exposed sediment and degree of scar-channel coupling in the (A) Burnhope and (B) Langtae stream systems.

(A)



(B)

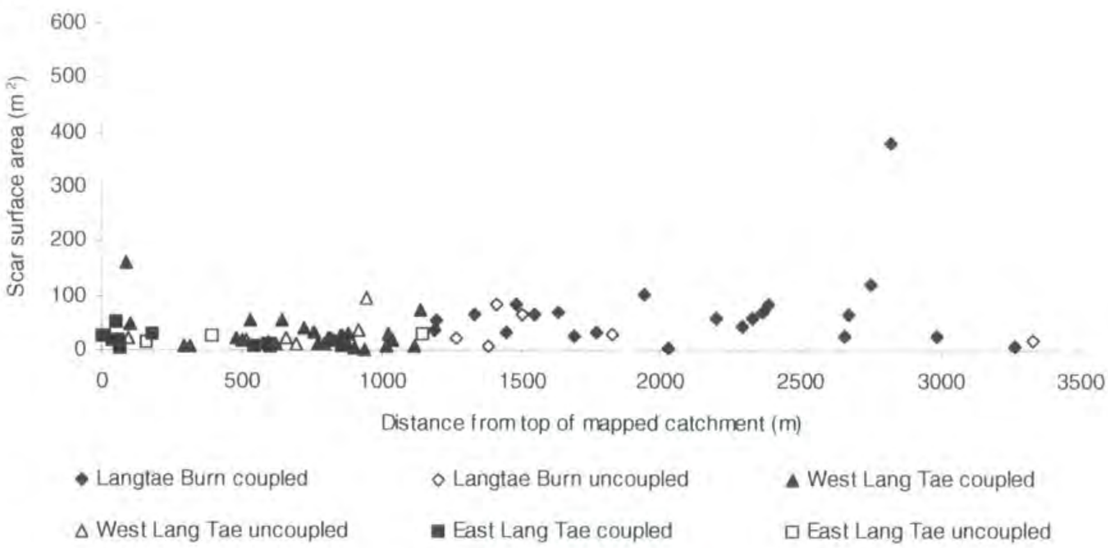
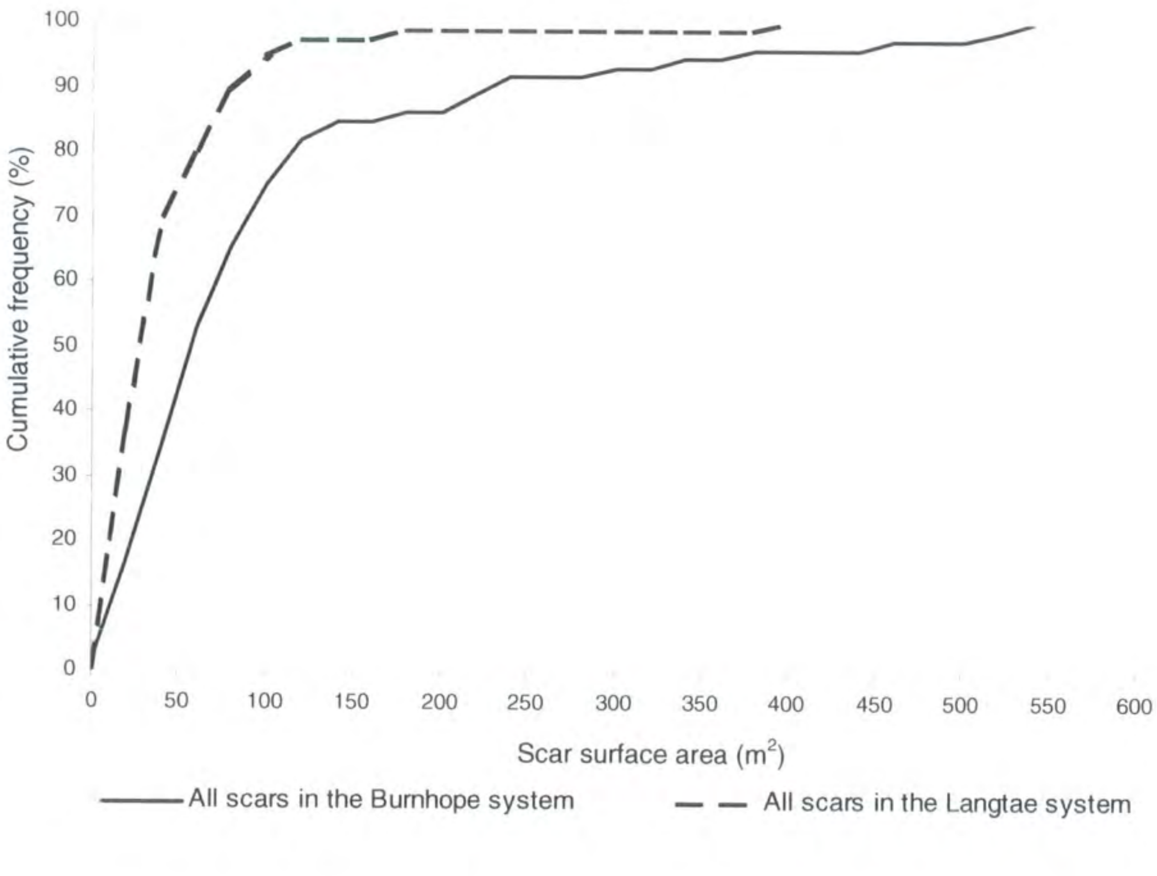


Figure 5.9 Stream-side scar located in the lower reaches of Burnhope Burn. Coupled indirectly to the channel during low flow and directly during moderate and high flows.

Figure 5.10 Cumulative frequency of surface area of all stream-side scars in the Burnhope and Langtae catchments.



The surface areas of all scars in the Burnhope and Langtae systems shown in Table 5.3 reveal that the total scar area in the Burnhope is twice that in the Langtae system, but on the basis that the Burnhope catchment is four times larger than Langtae it can be concluded that scar surface area and catchment area are not linearly correlated. Over 70% of scars in the Burnhope and Langtae catchments are coupled to channel but in an attempt to assess the potential for sediment supply from these sources it is necessary to compare ratios of stream length to stream-side scars. Table 5.4 assesses the degree of connectivity between coupled scars and the channel in the Burnhope system. A low ratio of stream length to stream-side scars indicates an increased potential for sediment supply. The ratios predict that for each 34.2 m of channel in Burnhope Burn, 1 m of exposed scar sediment is connected to the channel. In Scraith Burn there is 1 m of exposed scar sediment connected to the channel for every 10.8 m of channel. Scraith Burn also has 52% of the total area of scars coupled to the channel in the Burnhope system so potentially this tributary supplies a large proportion of the sediment in this system.

Figure 5.11 is a plot of length and height of coupled and uncoupled scars in the Burnhope system. Positive relationships are evident between height and length of coupled scars in the first order streams of Sally Grain and Scraith Burn. It is interesting to note that 93% of the largest scars contained in the dashed ellipsoid are coupled to the channel. It is likely that continuous erosion by stream flow is a contributing factor to scar development. Field observation of stream-side scars has revealed that scar height increases with scar length due to progressive failure of the bank face. Figure 5.12 is photograph of a scar on Langtae Burn exhibiting typical failures. There is a large re-vegetating mid-channel boulder berm in this reach of the channel deflecting the flow along the channel margins. The small scar feature to the left of the photograph has developed as a result of undercutting of a small length of the outer channel bank and failure of the surface material. Further undercutting along the length of this bank has resulted in the failure of a larger area of hillslope. As the basal length of the scar increases there is a larger area of sediment prone to instability.

Given the overall number of scars identified in the Langtae and Burnhope systems together with their connectivity to the channel, the potential sediment supply appears high from both catchments. When considering the age of these scar features it is interesting to note that approximately 95% of scars mapped from field observation are visible on the 1995 air photographs of the catchment. This raises questions regarding the freshness of scars. Due to the angle of the scars it is not possible to accurately measure their surface area from the vertical photographs, or assess their exposure

Table 5.4 Assessment of the degree of connectivity between scars and the channel in the Burnhope system.

Stream	Stream order	Total basal length of scars coupled to the channel (m)	Ratio of total channel length to basal length of coupled scars	Total area of scars with basal length coupled to the channel (m^2)
Burnhope Burn	2^{nd}	64	34.2	619
Sally Grain	1^{st}	322	11.1	1994
Scraith Burn	1^{st}	412	10.8	2780
Total		941	10.9	5393

Figure 5.11 The length and height of coupled and uncoupled scars in the Burnhope system. The black symbols indicate the 2^{nd} order streams while coloured symbols are the 1^{st} order streams.

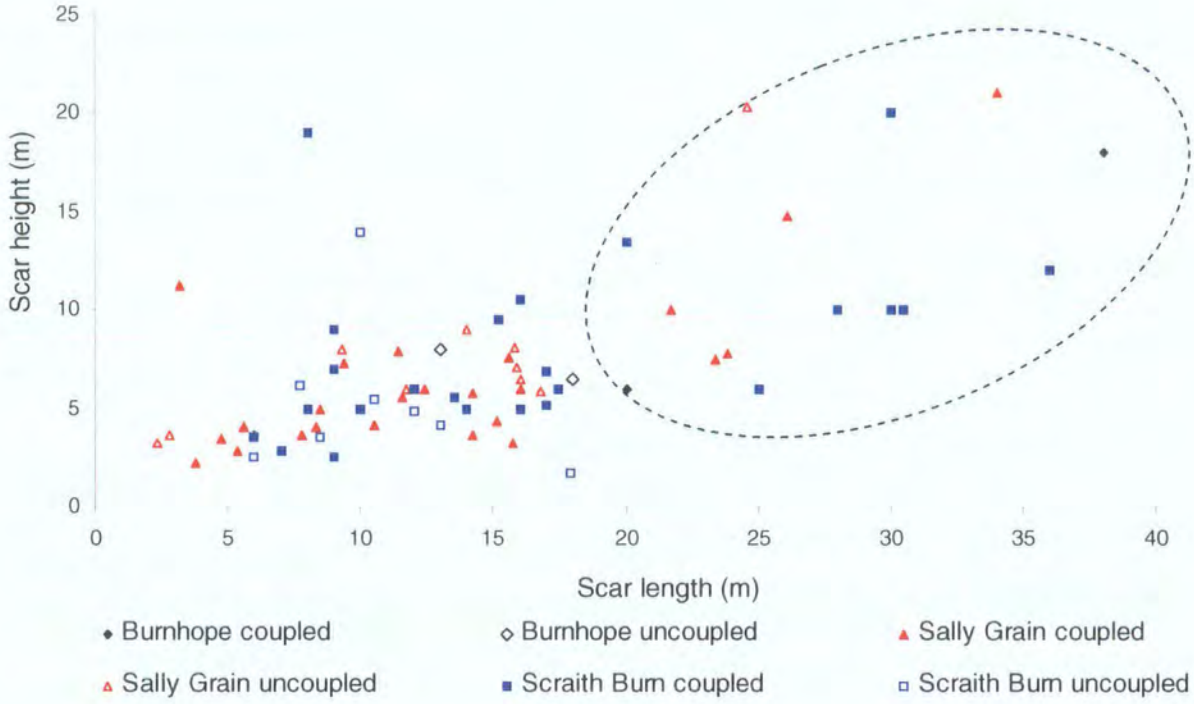
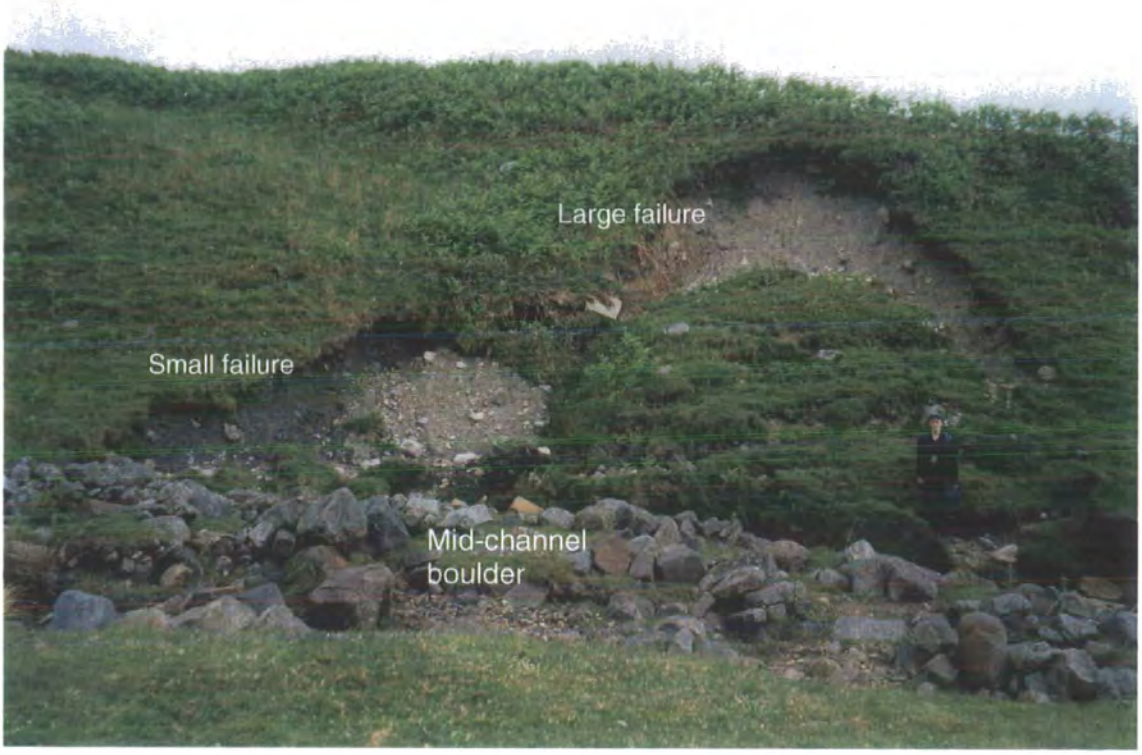


Figure 5.12 Variation in the area of scar features in comparison to length of cut bank, Langtae Burn.



based on degrees of re-vegetation. It is therefore difficult to assess variations in potential sediment supply from these sources over time. Gifford (2000) notes that the scars in Langtae are likely to be older than they first appear and that they are kept active by basal erosion of coarse-grained sediment and surface runoff causing surface wash.

5.3.2 Cut stream banks

Cut channel banks provide intermittent pulses of sediment from bank collapse and/or undercutting. These bank features are a potential sediment source during bankfull flow and being small in size are locally important in supplying fine sediment to the stream. Those features mapped as cut banks were sections of eroded/undercut channel bank that exceeded 1 metre in length. Figure 5.13 A and B are photographs of bank undercutting on the outside of bends on Scraith Burn and are examples of the types of features mapped as cut banks in the field. Figure 5.13 B shows a fresh bank collapse by undermining by the stream, forming an intermittent source of fine sediment directly to the channel. The collapsed bank also exposes a basal deposit with a fine sediment matrix supporting poorly sorted coarse sediment. Figure 5.13 C shows a face of exposed peat and boulder clay as the stream has incised and migrated laterally in the headwater reaches of Sally Grain. At low flow minerogenic sediments are directly coupled to the channel. During higher flow events the bank will be a source of both minerogenic and organic sediments. Table 5.5 provides a quantitative assessment of the degree of connectivity between cut banks and the channel in the Burnhope system. The ratio of total channel length to basal length of coupled cut banks are similar in both first and second order streams which indicates active lateral erosion of channel banks throughout the Burnhope system.

When comparing the relative importance of stream-side scars to cut banks in terms of basal length connectivity (and subsequent sediment supply to the stream), distinction can be made between the second and first order streams. The ratio of channel length to basal length of cut banks in Burnhope Burn is higher than the ratio of channel length to basal length of stream-side scars. A possible explanation for this is the decrease in channel confinement downstream so that the second order channel impinges in the hillslopes less but there is a greater tendency towards lateral migration and stream bank erosion downstream. The distinction between basal length of scars and cut banks to channel length in the first order streams is less significant. However, based

Figure 5.13 Stream banks showing (A) bend undercutting, (B) turf bank collapse by undercutting and (C) lateral incision through peat and boulder clay sediments.

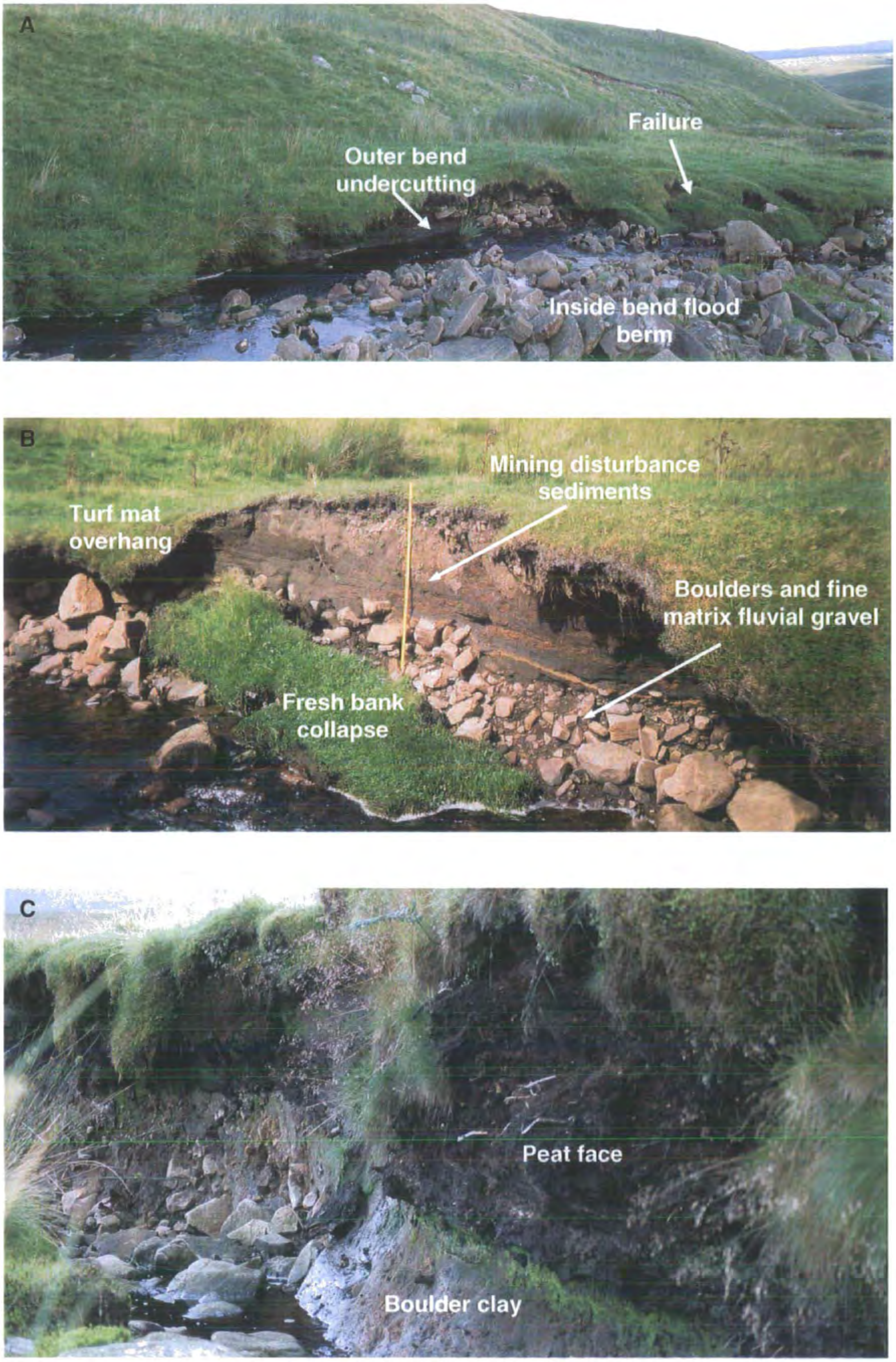


Table 5.5 Assessment of the degree of connectivity between cut banks and the channel in the Burnhope system.

Stream	Stream order	Total basal length of cut bank coupled to the channel (m)	Ratio of total channel length to basal length of coupled cut banks
Burnhope Burn	2nd	153	14.3
Sally Grain	1st	284	13.9
Scraith Burn	1st	318	14.1
Total		755	13.6

on the ratio of channel length to basal length of both features, stream-side scars are the greater potential sources of sediment to first-order channels.

5.4 Location of coarse-grained sediment storage in the Langtae and Burnhope catchments: boulder size variations downstream

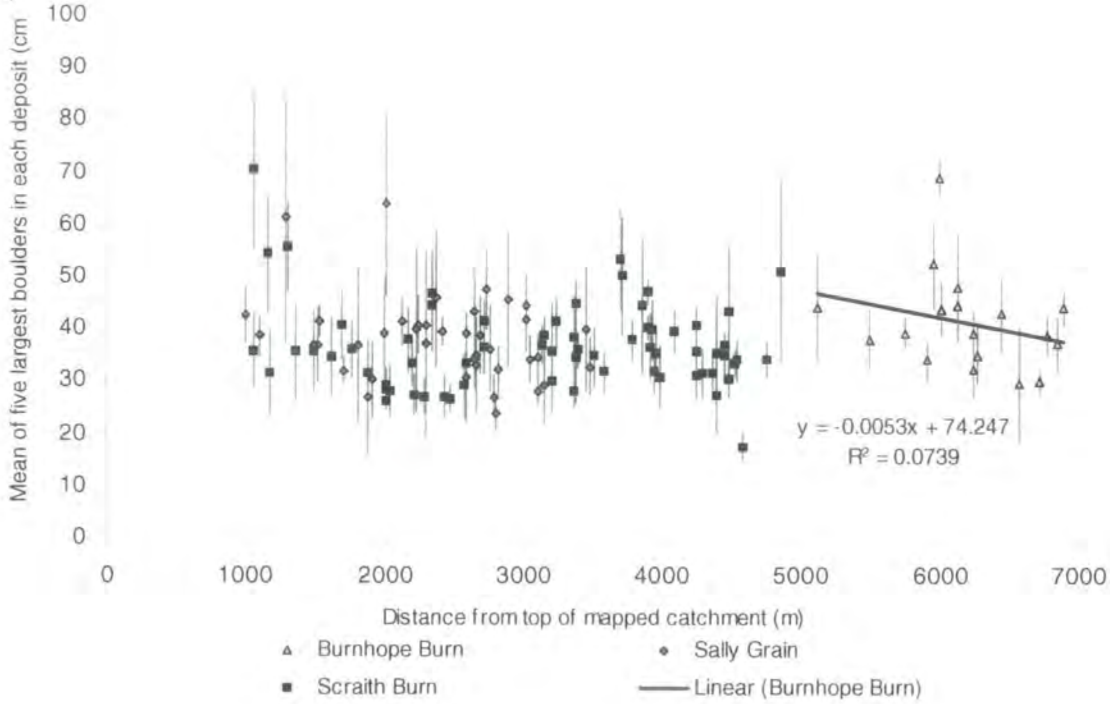
A flood deposit can be defined as coarse-grained sediments in storage either along the channel margins, mid channel or as berms and benches on floodplains. Flood deposits were identified in the field by assessing the morphology of each deposit and when a series of connected deposits were identified, each deposit was distinguished on the grounds of boulder size variations and the degree of re-vegetation of deposits.

The mean of five largest boulders in each flood deposit was measured and this has been plotted against distance from the top of the mapped catchment in the Burnhope (5.14 A) and Langtae catchments (Figure 5.14 B). These plots reveal different trends in boulder size downstream in the adjacent systems. The error bars on both plots represent one standard deviation either side of the mean and demonstrate the variation in size between boulders in each deposit. There is a slight variation in boulder size with distance downstream in the Burnhope catchment. The majority of deposits have a mean size of between 25 and 55 cm with the boulders in the headwaters being slightly coarser. However, on Langtae Burn from 1.1 km there is a general decrease in mean boulder size with distance downstream. The relationship is not particularly strong accounting for only 33% of the variance in boulder size (Gifford, 2000). This reflects the local variability between stream reaches. The majority of boulder sizes on Langtae are of similar size as those on Burnhope Burn but at a few sites in the Langtae system average boulder sizes exceed 60 cm. Gifford (2000) attributes the increase in larger boulders at this point to the increase in potential supply of suitable material from mining activity on East Lang Tae and the high stream gradient and intermediate valley floor width along West Lang Tae. Variations in supply of sediment from lateral inputs and the geometry of the valley determine the distribution and size of boulders deposited.

In both catchments there is a lack of boulder deposits in the headwater reaches. The first 1000 m and 500 m in Burnhope and Langtae respectively are devoid of major deposits. This is due to the nature of material into which the channel is incised. Peat predominantly occurs at the head of both catchments with solifluction, boulder clay and reworked mining sediments dominating further downstream. Figure 5.15 shows photographs taken on a reach of a tributary channel feeding Sally Grain in the

Figure 5.14 Variations in mean boulder size with distance downstream in the (A) Burnhope system and (B) Langtae system.

(A)



(B)

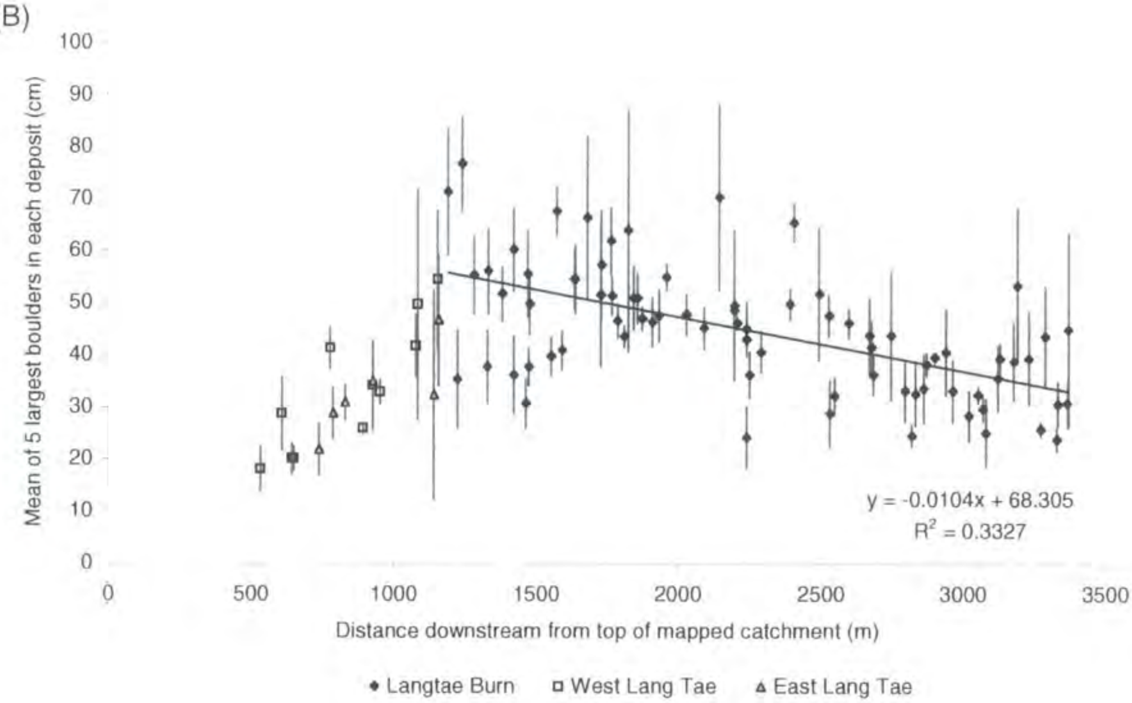


Figure 5.15 Photographs of a reach of a tributary stream feeding Sally Grain. (A) Peat incision and (B) subsurface drainage causing collapse of gully heads in the peat.

Burnhope system (Figure 5.1). These photographs show ephemeral tributaries emerging from the blanket peat and collapse structures at the channel head. The ephemeral streams in this example feed Scraith Burn (Figure 5.1).

It was evident from field observations and air photograph interpretation that the location of boulder deposits relative to the channel varied with distance downstream. In the headwater reaches these deposits were located in the active channel while further downstream, as the channel widened and there was increased valley-floor storage potential, flood deposits from previous events formed berms and benches above the present channel. Figure 5.16 A shows various floodplain berms and benches on the inside of a bend whilst Figure 5.16 B shows re-vegetation of super-elevated boulder deposits. By mapping the spatial extent of these deposits it was possible to assess the degree of lateral and vertical activity of the channel. Attempting to establish a chronology for these deposits helps to determine temporal scales of sediment transfer in these catchments.

5.5 Establishing a chronology for flood deposits in the Langtae and Burnhope catchments

As discussed in Chapter 4, Section 4.3.2, lichenometry was used to estimate the age of flood deposits. The technique relies on the basic assumption that lichen thalli size is directly related to substrate age (Merrett and Macklin, 1999). Lichens were measured using the same sampling strategy for the Burnhope and Langtae systems. Of the 136 boulder deposits recorded in Burnhope Burn and the tributary streams, Sally Grain and Scraith Burn, lichens were measured on 48 deposits. The remaining unmeasured deposits were either clean of *Rhizocarpon* lichens or re-vegetated to a degree where thalli were no longer visible. Lichens were measured on 86 of the 103 boulder deposits in the Langtae catchment, which include *Rhizocarpon* and *Lecanora* lichens.

Figure 5.17 shows the size frequency of the mean diameter of the five largest lichens on each deposit in the Burnhope catchment. For the whole Burnhope system (Figure 5.17 A), there is a general trend of decreasing frequency with increasing size of *Rhizocarpon* thalli. There are two peaks in lichen size frequency between 26 and 30 mm and 36 and 40 mm that interrupt this general trend. Individual size frequency histograms are plotted for each section of the Burnhope system, for the first order tributaries of Sally Grain, Scraith Burn and second order Burnhope Burn (Figure 5.17

Figure 5.16 Re-vegetated flood deposits on (A) channel margins and (B) floodplain berms and benches on the inside of a stream bend in Scraith Burn.

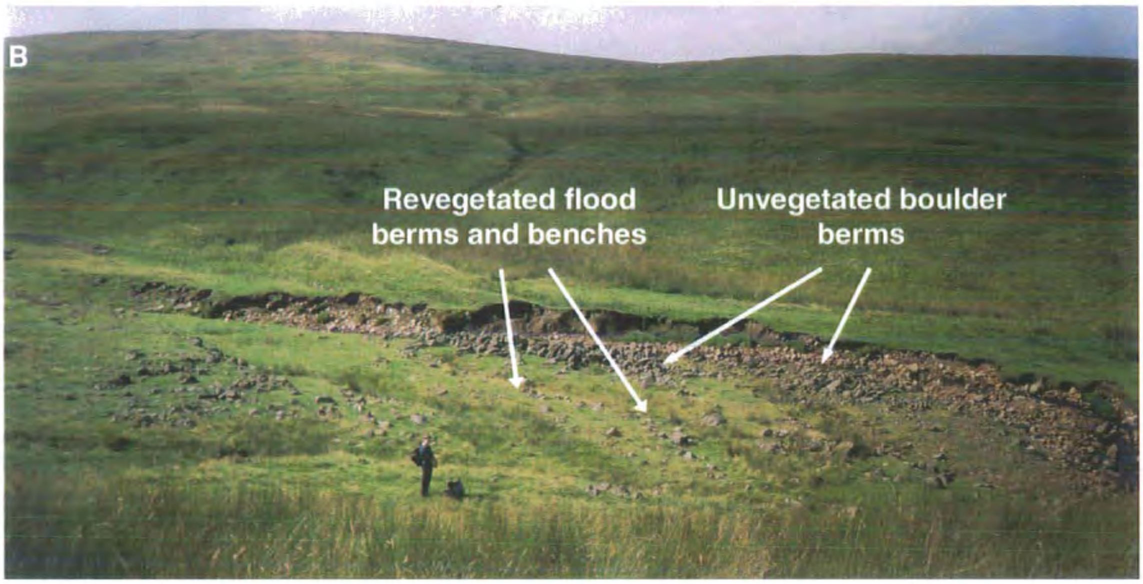
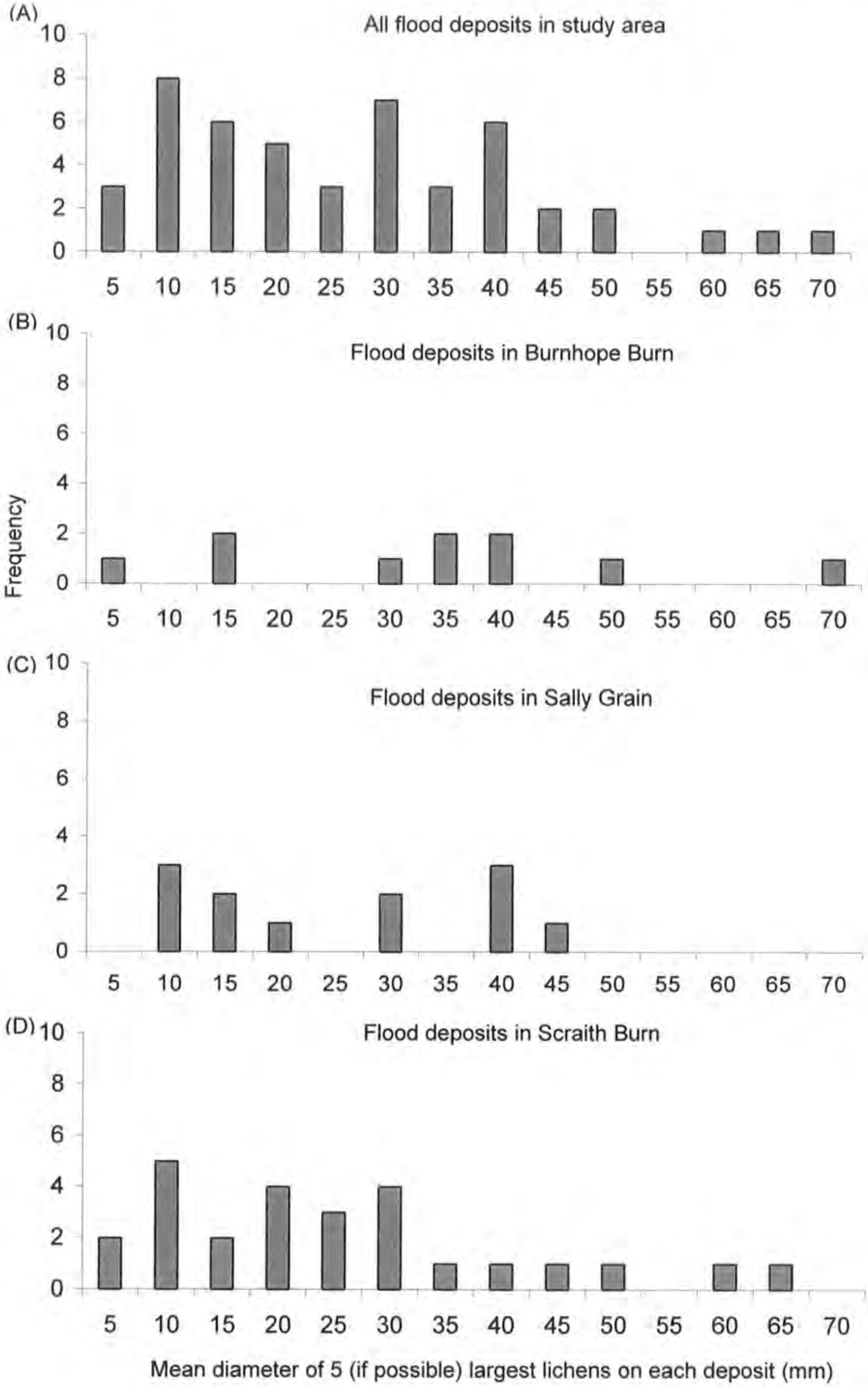


Figure 5.17. Size frequency of *Rhizocarpon* on flood deposits in the Burnhope system.



B, C and D). Sub-sectioning the data in this fashion reveals the generally low frequency counts of *Rhizocarpon* lichens in the Burnhope system, particularly in Burnhope Burn and Sally Grain. This must be taken into consideration when determining chronologies for flood deposits in the Burnhope system. When comparing the histograms from individual streams with that of all flood deposits (Figure 5.17 A) it is clear that the overall size distribution of lichen diameters is mostly influenced by thallus measurements from Scraith Burn. This is because over 50% of the lichens measured were located on Scraith Burn. It is useful that the majority of lichens were measured on this tributary as it is the longest channel in the system and provides the clearest representation of sediment movement with variation in gradient, channel width and mining disturbance. Approximately 77% of deposits in Scraith Burn have thallus diameters between 1 and 34 mm that skew the overall distribution towards smaller lichens. As thallus size is a proxy for substrate age the general trend in the Burnhope system is towards a majority of younger deposits with older deposits being in the minority. This is expected given the weighting of measurements taken from a tributary channel with active sediment transfer.

In the Langtae system Gifford (2000) found a unimodel distribution of *Rhizocarpon* with the most frequently observed size class between 35 to 40 mm. However, due to the lack of identifiable *Rhizocarpon* lichens in the tributary streams of the Langtae system, *Lecanora* thalli were also measured (Gifford, 2000). Figures 5.18 A and B show the size frequency histograms for *Rhizocarpon* and *Lecanora* lichens on flood deposits in the Langtae systems. The most common size frequency of Lecanora are between 10-20 and 30-40 mm. When Figure 5.18 A is compared to the overall trends of *Rhizocarpon* thalli in the Burnhope system (Figure 5.17 A), there are overall similarities in size range and frequency of the 30-40 mm band between the two catchments. However, the overall low counts of *Rhizocarpon* in the Langtae system limit the degree of comparison between the systems.

To evaluate the spatial distribution of thallus diameters on deposits in relation to distance downstream, the mean diameters of the five largest lichens on each flood deposit has been plotted against distance from the top of the mapped catchment and the relationship between these parameters is shown in Figure 5.19. Figure 5.19 A shows the distribution of *Rhizocarpon* lichens in the Burnhope system while Figures 5.19 B and C are *Rhizocarpon* and *Leconara* in the Langtae system. The error bars represent one standard deviation either side of the mean of the largest lichens on each deposit. The error bars are important because lichen diameter is a proxy for substrate age and so large variations in thallus diameter translates into large variations in relative

Figure 5.18 Size frequency of (A) *Rhizocarpon* and (B) *Lecanora* on flood deposits in the Langtae system.

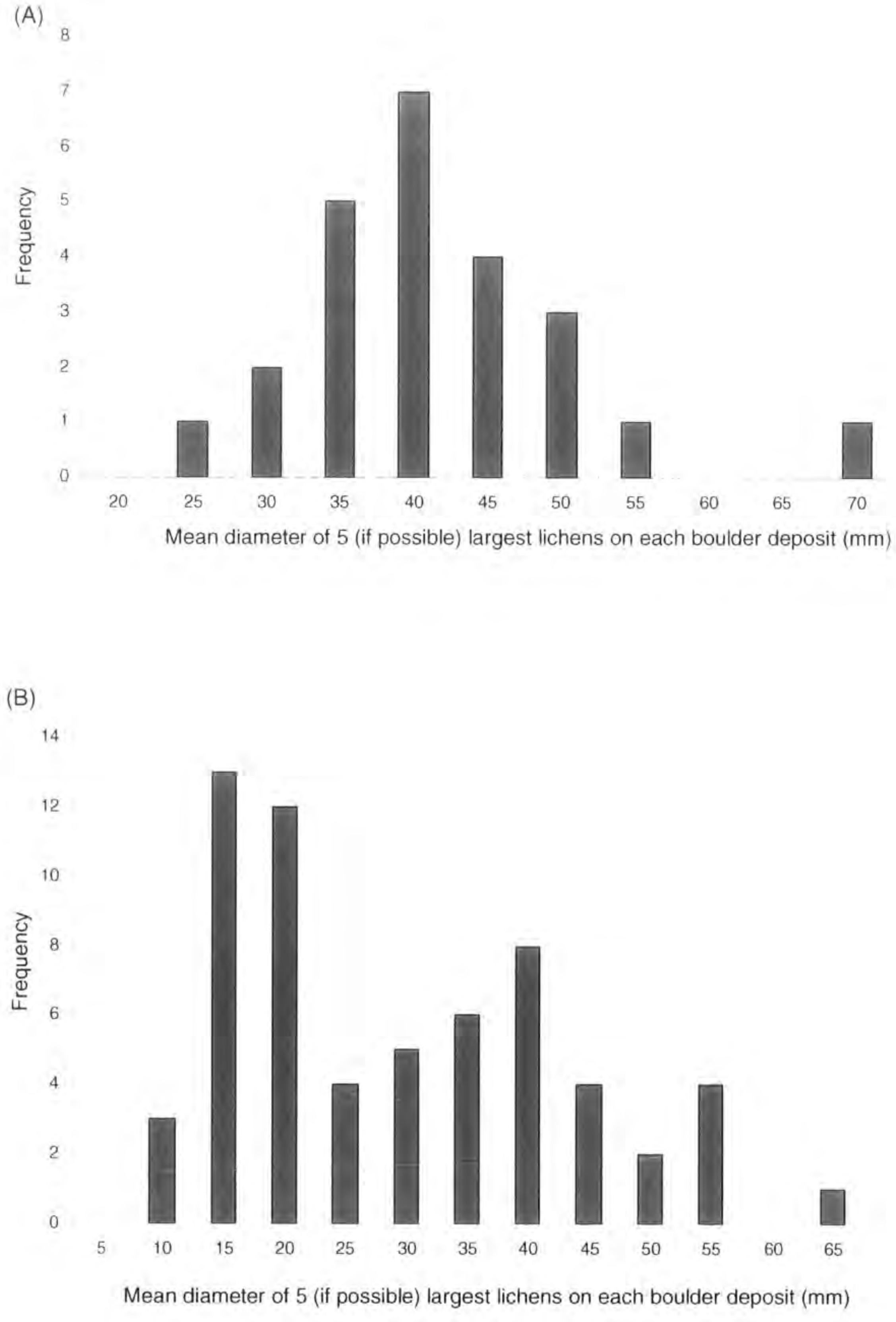
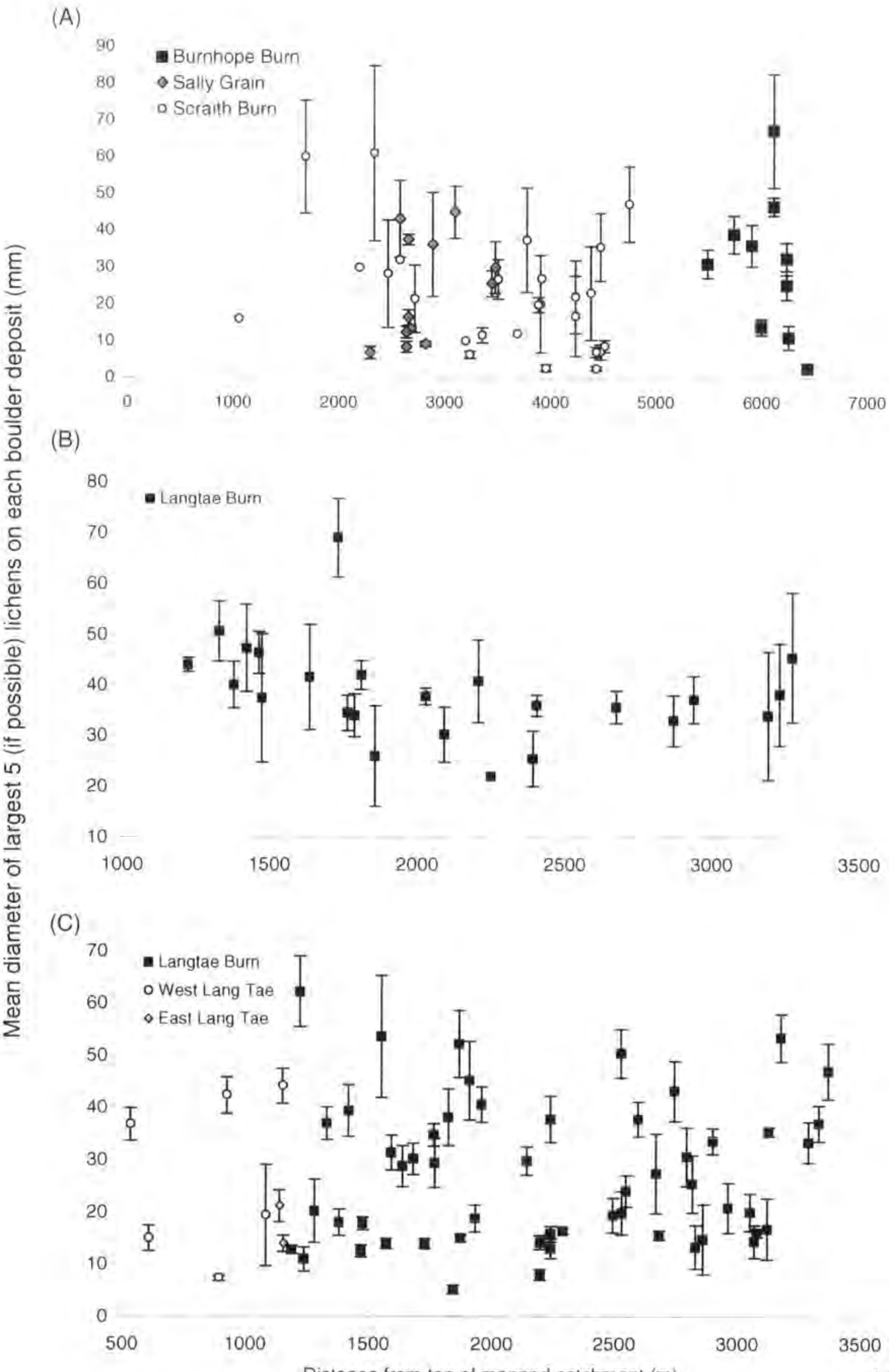


Figure 5.19 Mean diameter of the five largest *Rhizocarpon* lichens on each flood deposit against distance downstream in the (A) Burnhope and (B) Langtae catchments and (C) *Lecanora* lichens in the Langtae system.



(and absolute) age estimates of the deposits (Locke *et al.*, 1979). The variability in the results indicates that there is no downstream trend in substrate age and the range of age estimates is fairly evenly distributed downstream in both catchments. It is clear that these deposits have been formed by a number of flood events over time.

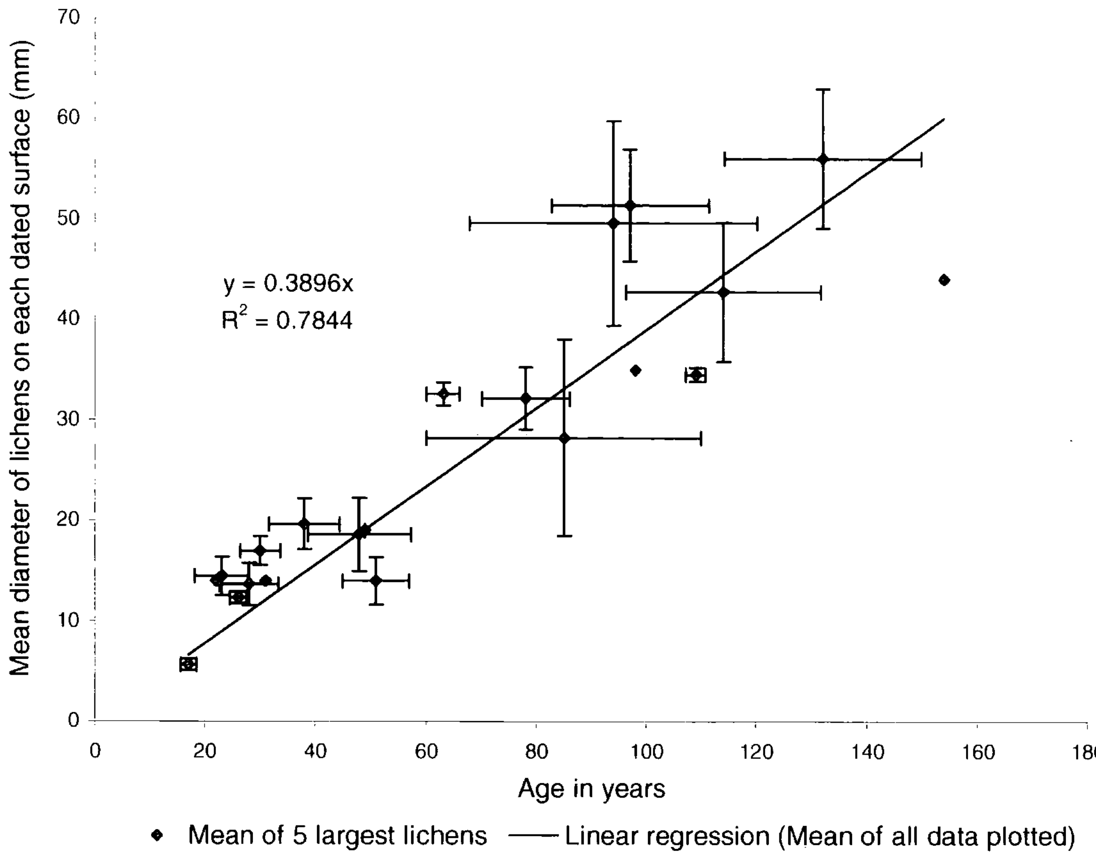
5.5.1 Determining absolute ages of flood deposits

In order to ascertain absolute age estimates for Rhizocarpon lichens on boulder deposits in the Burnhope and Langtae systems, it was necessary to determine a growth rate from substrates of known age. As described in (Chapter 4), Section 4.3.2, lichens were measured on gravestones at Burtreeford Bridge cemetery. Gifford (2000) produced an age-versus-size curve for *Rhizocarpon* lichens using this method and the results are shown in Figure 5.20. To obtain comparable results from gravestones and flood deposits, the mean was taken of the five largest lichens measured and plotted against the age of the gravestone. Where there were fewer than five lichens measured the mean of the remainder was still considered valuable; as the surface area of gravestones are small in comparison to flood deposits (Gifford, 2000), these points are marked with open symbols on Figure 5.20. The error bars in the age-versus-size curve represent one standard deviation either side of the mean. The vertical bars relate to variations in lichen diameter and horizontal lines represent variations in the age estimates of the lichens. Those symbols with no error bars are based on single lichen measurements.

The regression plot provides a growth rate of 0.39 mm yr^{-1} for the *Rhizocarpon* lichens. This rate is comparable to those results reported by Macklin *et al.* (1992a) in Thinhope Burn, North Pennines and Merrett and Macklin's (1999) figure of 0.36 mm yr^{-1} in the Yorkshire Dales (Gifford, 2000). These growth rates along with others used in upland systems have been summarised in Table 4.1.

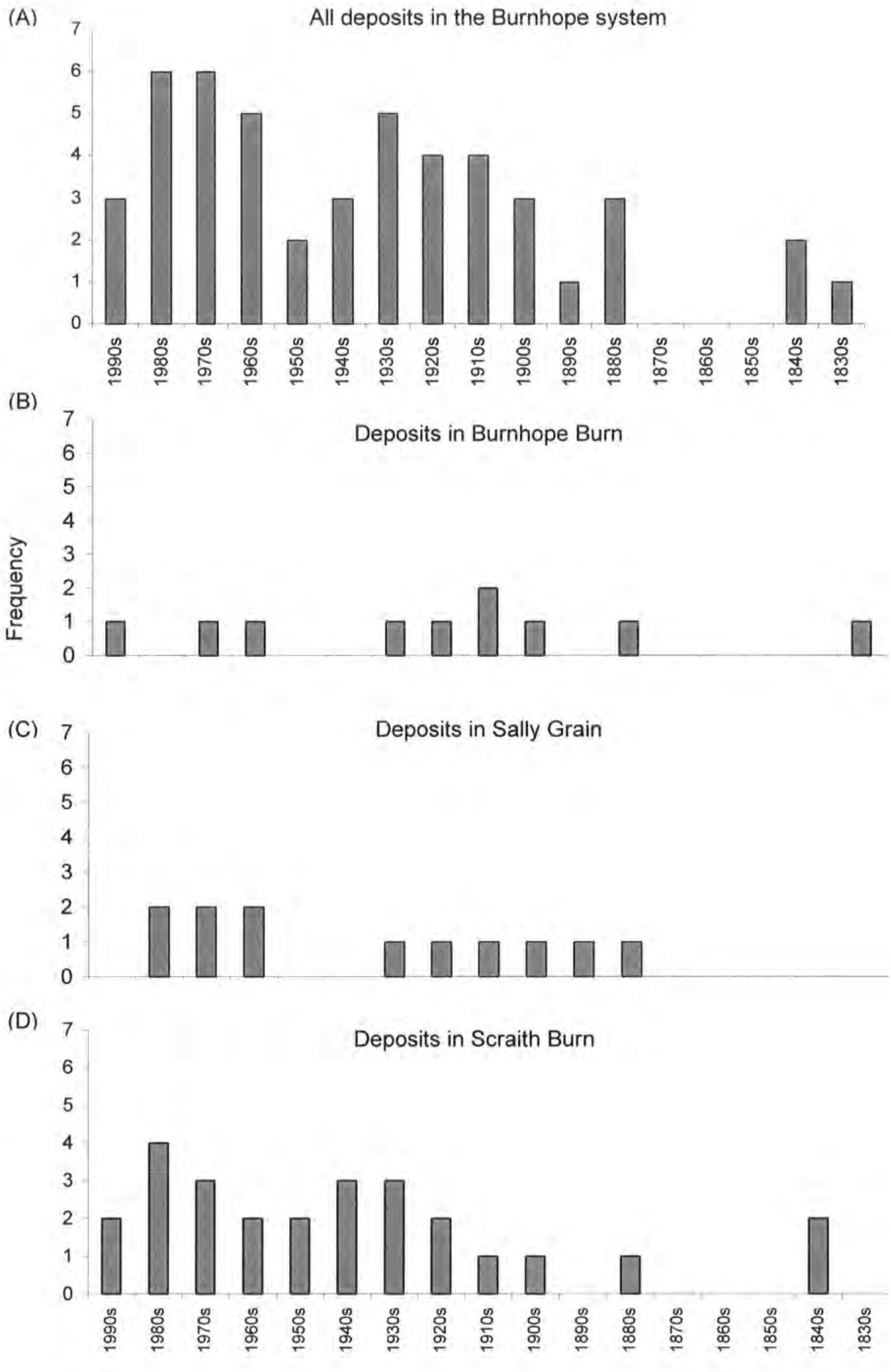
Based on this growth rate estimate of 0.39 mm yr^{-1}, the relative age estimates based on lichen thallus diameter in the Burnhope and Langtae systems can be converted to absolute age estimates. Gifford (2000) reported that the exact conversion procedure is rarely carried out in published studies and notes the importance of accounting for the natural variability in lichen growth rates on flood deposits and on gravestones by considering the range of results shown by the error bars. Figures 5.21 A, B, C and D show the age of flood deposits in the Burnhope system dated using *Rhizocarpon*.

Figure 5.20 Age-verses-size plot for *Rhizocarpon* lichens from Burtreeford Bridge cemetery.



Modified from Gifford (2000)

Figure 5.21 Age of flood deposits in the Burnhope system dated using *Rhizocarpon*.



There is a gradual decreasing trend in the number of deposits recorded with age, from the most contemporary deposits of the 1990s to the oldest deposits dated to the 1830s. The reasons for this trend are three-fold:

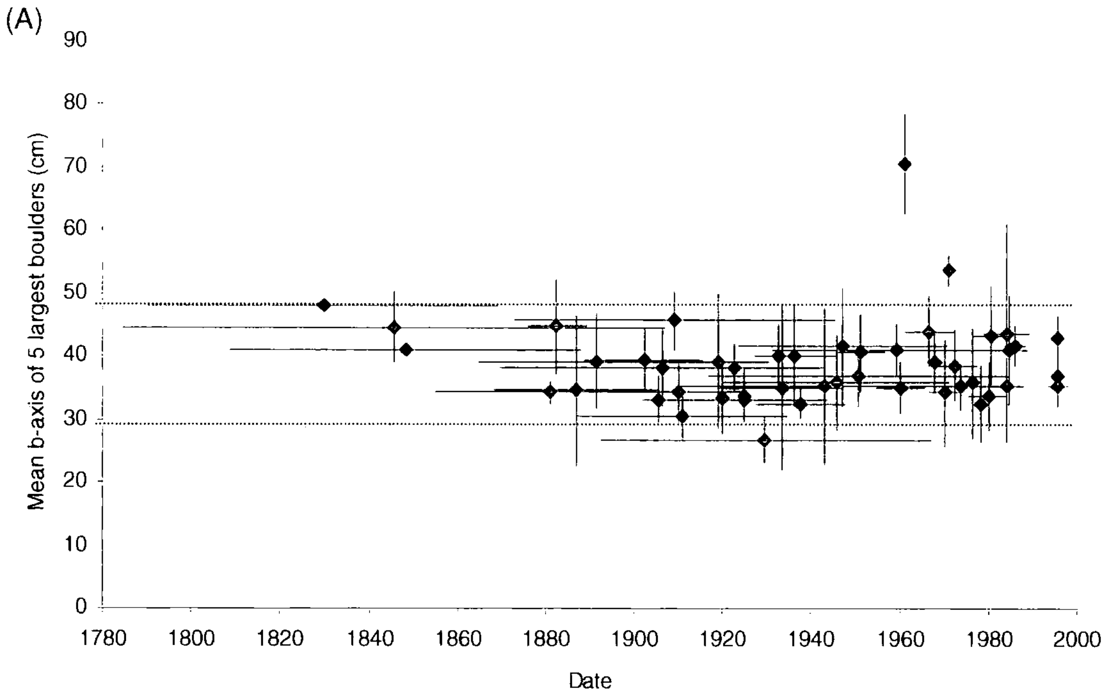
1. Issues of deposit preservation in confined channel resulting in reworking of boulder deposits
2. Re-vegetation of older deposits
3. Variations in rainfall patterns over time resulting in variations in flood magnitude and frequency.

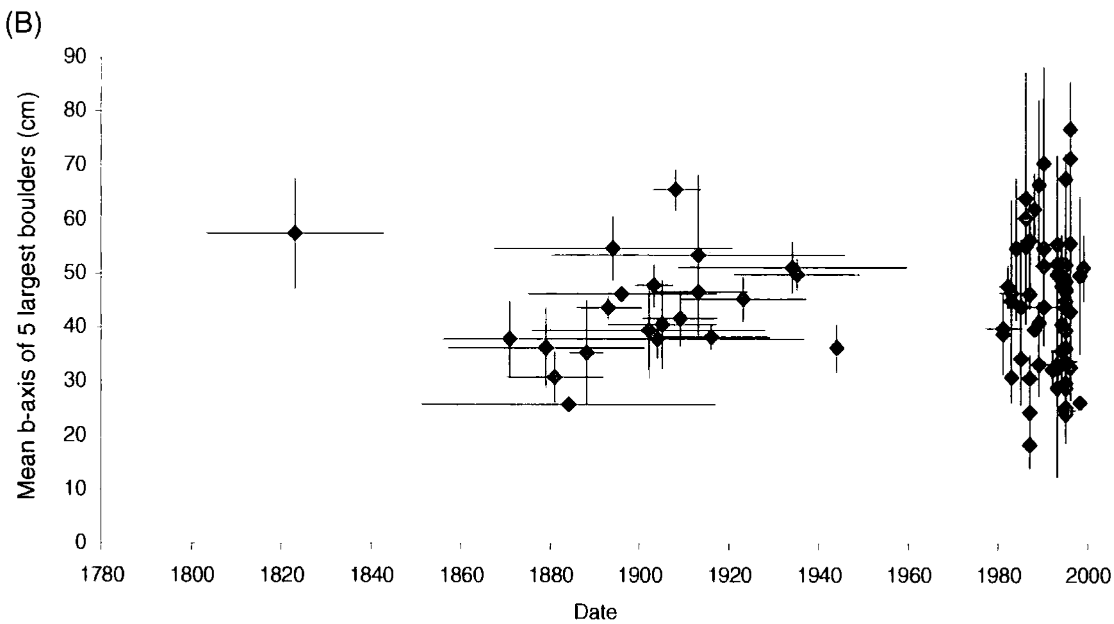
These causes cannot be assessed in isolation, as the forces controlling the preservation of deposits are often a combination of channel morphology, flood magnitude and frequency and human interference. There are a number of interesting exceptions to the general trend of decreasing frequency of deposits with age. The most notable variation is the lack of deposits over the twenty-year period between the 1850s and 1870s. The peak in mining activity in this region occurred from the 1860s to the 1880s before finally petering out in the early 1900s (Warburton, 1998). There was significant local disturbance and removal of flood deposits during this mining period due to the construction of tracks on floodplains and channel boundaries and the dredging of channel boulders for use in construction of mine buildings, the relics of which are still visible today. This period of extensive disturbance in Sally Grain and Scraith Burn could explain the lack of flood deposits recorded before the turn of the century.

Figure 5.22A and B show the relationship between boulder size and age of deposit in the Burnhope and Langtae systems respectively. Figure 5.22A shows a general consistency in b-axis measurements of boulders dated from the 1800s to late 1990s. The sizes of the mean largest boulders vary by only 20 cm throughout the Burnhope system. This consistent size range could reflect transport capacity limitation or underestimation of boulder sizes due to re-vegetation of older flood deposits. It is unlikely to reflect sediment supply limitation as field observations recorded large numerous boulders and sections of eroded bedrock that remain in situ in the channel.

In contrast Figure 5.22 B reveals clustering of flood deposits and a greater range of sizes of b-axis measurements in the Langtae system. From this plot it is evident that there are three periods of preservation of deposits. Firstly a single deposit from the 1820s followed by several deposits from the 1870s to 1940s and a peak at the turn of the century. The third cluster of deposits is dated post-1980 with a notable

Figure 5.22 Plots of mean b-axis measurements of boulder deposits with age (between 1823 and 1997) in the (A) Burnhope and (B) Langtae systems.





concentration in the early to mid 1990s. Gifford (2000) discussed possible reasons for the lack of deposits between the 1830s to 1870 and 1945 to 1980. These reasons included reworking by more recent flooding, the lack of floods from 1945 to 1980, the problems of deposit preservation and the issues of using a multi lichen species approach to dating deposits.

From comparison between Figure 5.22 A and B it is clear there are differences in boulder sizes in both systems. The range in boulder size distribution is much greater in the Langtae system. The reason for this variation between adjacent systems could be due to less re-vegetation of larger boulder deposits due to more frequent inundation of deposits in the smaller Langtae system and differences in sediment supply and transfer. Gifford (2000) commented on the high concentration of large boulders dating from the mid-1980s to mid-1990s that could be older boulders deposited in the active channel that have been periodically inundated by flow, resulting in retarded lichen growth. In the work of Macklin *et al.* (1992a) b-axis measurements in the mid to late 1800s were used to reflect a decrease in flood competence over the past 200 years. It was acknowledged that variations in boulder transfer could be due to the availability of very large clasts for transport.

5.6 Comparison between age of deposits and rainfall records

Having established the age ranges of the flood deposits it is possible to compare these ranges with long-term rainfall records. Figure 5.23 shows the annual rainfall totals as residuals of the mean recorded at Wearhead Water Treatment Works between 1936 and 1998. Mean annual rainfall for the 62-year record is 1289 mm but annual totals have fluctuated above and below this mean value. The trend indicates above-average totals for the majority of the 1940s. The year 1954 is the wettest on record and from the mid-1950s to the early 1980s the majority of annual rainfall is below the mean with early 1970s recording the direst years on record. From the mid-1980s to 1998 the trend is towards annual totals greater than the mean. More detailed analysis of this rainfall record is shown in Figure 5.24 that provides the record of residuals of mean daily totals from 1936 to 1998. Despite peaks in daily rainfall recorded in the mid 1940s and early 1960s there is no obvious trend evident from daily rainfall totals from 1936 to 1998. It is interesting to note that despite the 1970s recording lower than average annual rainfall totals, the largest daily rainfall totals were recorded in the mid to late 1970s. Table 5.6 lists the top 20 maximum daily rainfall totals recorded from 1936 to 1998. The top three were recorded in the mid to late 1970s, two occurring during the

Figure 5.23 Annual rainfall totals as residuals from the mean recorded at Wearhead Water Treatment works from 1936 to 1998.

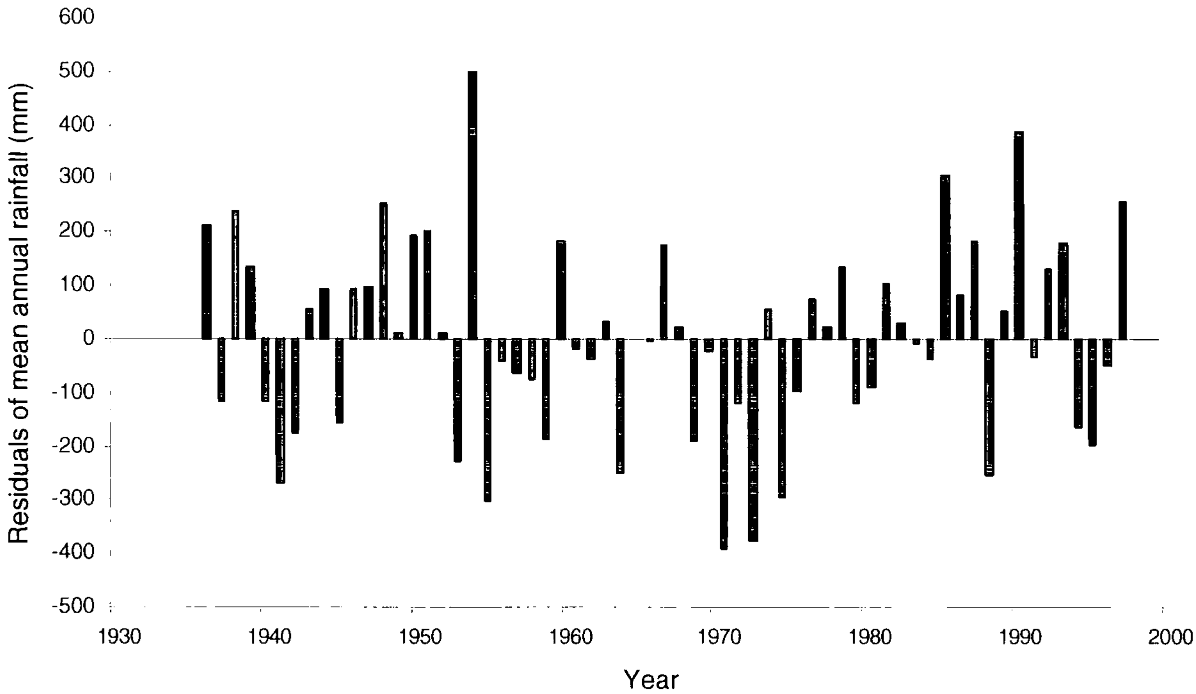


Figure 5.24 Daily rainfall totals as residuals from the mean recorded at Wearhead Water Treatment works from 1936 to 1998.

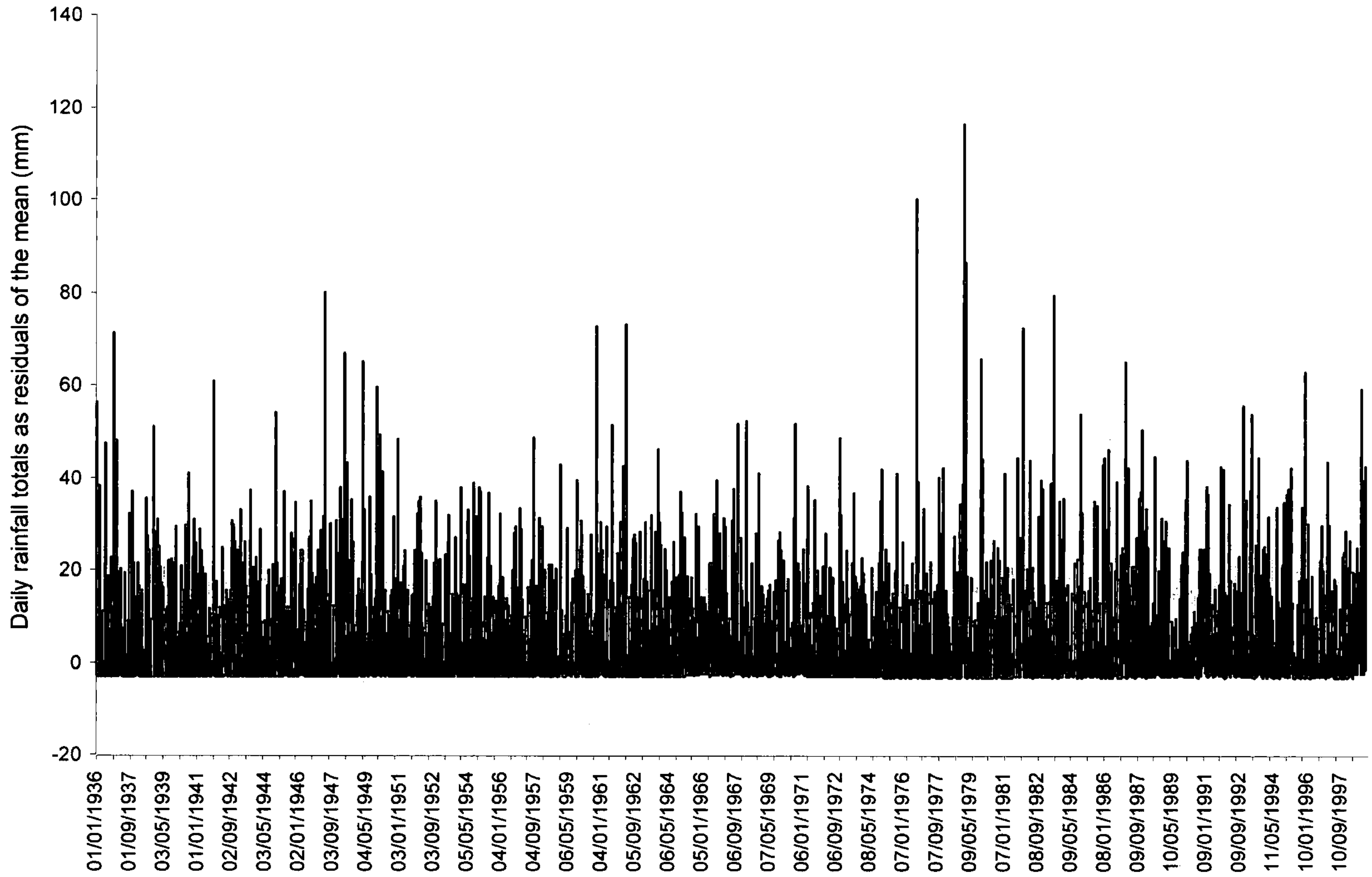


Table 5.6 Top 20 maximum daily rainfall totals recorded from 1936 to 1998.

Date	Rainfall total (mm)
31/01/79	120
11/09/76	103.7
28/02/79	90
21/04/47	83.8
17/07/83	83
02/04/62	76.7
09/10/60	76.2
31/12/81	76
24/10/36	74.9
31/03/48	70.6
25/11/79	69.4
31/01/87	68.8
22/02/49	68.6
31/12/95	66.5
09/10/41	64.5
12/11/49	63.2
25/10/98	63
09/01/36	59.9
01/12/92	59.1
04/11/44	57.7

winter months and one as a result of a convective summer event. Table 5.7 summarises the number of days recording daily rainfall totals within the top 50 maximum daily falls between 1936 and 1998. Aside from the high number of days recorded in the 1940s, 54% of events in the top 50 maximum daily falls were recorded from the 1970s to the 1990s.

These rainfall statistics are then compared to the record of flood deposits in Figure 5.25 to assess whether broad variations in flood deposit chronology can be related to rainfall events. Daily rainfall records for the catchments are the highest resolution data available and although not ideal for assessing the intensity or duration of flood events, can be a useful gauge for relating observed deposits with rainfall records. Antecedent conditions and storm magnitude, intensity and location are all key parameters that influence the geomorphic effectiveness of each event. Records of these parameters are limited to human observation and monitoring that are both limited in upland regions.

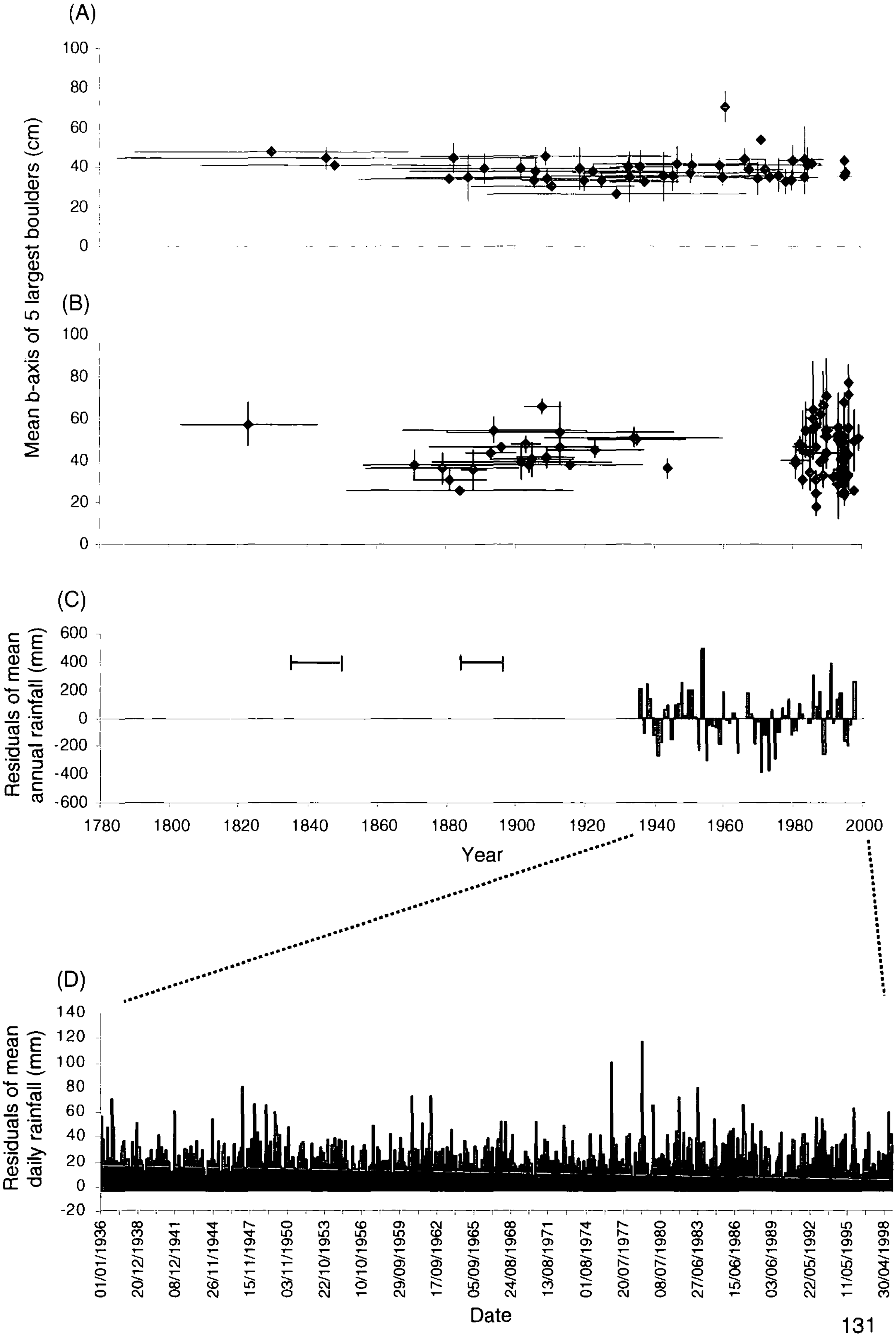
When considering the Burnhope system as a whole, 52% of deposits have been assigned dates from 1938 to 1997 (Figure 5.22A and 5.25A and C). These deposits fall in the date range of the rainfall record. Approximately 33% of deposits were dated between 1899 and 1923, which is unfortunately outside the scope of the rainfall record at Burnhope (5.25C). The most frequently occurring age range was 1976 to 1985 that compares to the period in the daily rainfall series with higher than average daily rainfall totals (Figure 5.25D). The biggest 24-hour rainfall event in the Burnhope rainfall series (1936-1988) was recorded on 01/02/79 with a total of 120 mm (Table 5.6). Flood deposits of this age range were found in both tributary streams but not in Burnhope Burn (Figure 5.21). A reason for this could be because the boulders moved during the event were deposited in the lower reaches of the Burnhope channel and have been subsequently reworked during periods of channel engineering in the 1990s, or by subsequent flows.

According to the rainfall record in Figure 5.25D and Table 5.6, the event recording the maximum daily intensity of rainfall since the event in 1979 occurred four years later in 1983 with an intensity of 83.0 mm. This was an extreme event with a return period of 400 years (NERC, 1975) where the daily total fell over a three-hour period. No further events of such magnitude occurred which could explain the preservation of deposits from the 1979 to 1987 period. The next most frequent age range was between 1925 and 1935. Deposits from this range were found in all three streams but without corresponding local rainfall data it is difficult to expand further.

Table 5.7 Number of days recording daily rainfall totals within the top 50 maximum daily falls recorded between 1936 and 1998.

Decade	Number of days
1930	5
1940	9
1950	3
1960	6
1970	7
1980	11
1990	9

Figure 5.25 Plots of mean b-axis measurements of boulder deposits with age (between 1823 and 1997) in the (A) Burnhope and (B) Langtae systems in relation to the (C) annual and (D) daily rainfall record from 1936 to 1998. The red lines indicate phases of increased rainfall in the Tyne basin.



Comparison between rainfall events and flood deposits in Langtae is problematic due to the lack of deposits dated between 1945 and 1980. The deposits dated 1981 to 1985 have been tentatively related to the Noon Hill flash storm event that occurred in July 1983 (Carling, 1986b) on the basis of high daily rainfall totals during this event and due to the lack of other significant 24-hour rainfall totals during this time period (Gifford 2000). The deposits dated to the mid-1990s do not correspond to any significant rainfall events in the Burnhope record. Gifford (2000) suggested that these deposits could be related to winter floods involving snowmelt runoff such as the January 1995 event in Swinhope Burn, North Pennines (Warburton and Danks, 1998). Alternatively these deposits could be older than they appear and their location in the channel has resulted in frequent inundation retarding lichen growth.

In an attempt to investigate the relationship between the oldest flood deposits in the Burnhope and Langtae systems and rainfall records outside the range of those from the Burnhope Treatment plant it is possible to use regional rainfall records. Rumsby and Macklin (1994) used a number of homogenised regional precipitation series to give a general indication of the prevailing surface moisture budgets for the Tyne Basin from the mid-19th century. Correlating trends in annual totals from the 1936-1998 Burnhope rainfall series with those from the Tyne basin proposed by Rumsby and Macklin (1994) resulted in broad similarities between records over the 20th century (Gifford, 2000). As a result of this correlation it is possible to assume that relative trends in annual precipitation from the Tyne basin could be representative of general trends in the Burnhope catchment. Two phases of increased rainfall were recorded during 1825-1839 and 1875-1885 (Lamb, 1977; Harris, 1985; Archer, 1992) and a clustering of major floods during 1828-1831 and 1881-1886 (Rumsby, 1991; Archer, 1992; Rumsby and Macklin, 1994). These periods are recorded on Figure 5.25 as red lines for ease of comparison to the dated deposits. Three deposits in the Burnhope, and a single deposit in the Langtae catchment have been dated between 1820s and the mid 1840s that could correspond to these increased rainfall totals. These trends must be treated with caution as Rumsby and Macklin (1994) state that the areal coverage of flood records for the Tyne is more comprehensive for the lower reaches of the catchment and events in the headwater reaches are probably under-represented (Rumsby and Macklin, 1994). However, in the absence of other available rainfall data, broad comparisons may be drawn with awareness of these limitations. It must be noted at this point that major floods in the Burnhope catchment can also be generated by winter rainfall events, snowmelt and convective summer thunderstorms that are unrelated to broad trends in climate change and are often poorly characterised by total daily rainfall statistics.

The sediment sources, sinks and zones of transfer have been identified for the Burnhope and Langtae systems. Dating of flood deposits identifies a general decrease in the number of deposits with age. This is attributed to reworking of deposits by storm events and re-vegetation of older deposits above channel-margins. Gaps in the lichen records between 1850-1880 were found in both systems and could be attributed to mining disturbance in both catchments. The gap between 1945 and 1980 in the Langtae record was not found at Burnhope, which supports Gifford's (2000) argument that this corresponds to the divide between the dating of younger deposits and older deposits using different lichen species. The limitations of using licenometry as a rapid assessment tool in these catchment surveys result in large error ranges on dated deposits. However similarities between Burnhope and Langtae suggest coarse-grained sediment transfer occurs regularly and is not restricted solely to extreme events recorded in rainfall records.

Understanding the links between high rainfall events or periods of high rainfall and coarse-grained sediment transport is important in terms of the timing of sediment movement in the channel. The transfer of coarse sediment is important in terms of removal of toe deposits and subsequent activation of streamside scars or undercutting of channel banks.

5.7 Temporal variations in sediment supply and overall channel stability

Temporal variations, over decadal timescales, of fine sediment supply from scar faces and the supply of coarse-grained sediment from lateral incision of channel banks and stream-side scars is difficult to assess without detailed process measurements. Harvey (1977) measured sediment yields from individual gully slopes over time and assessed the seasonal effects on hillslope stability and sediment supply. Photographs taken at six-monthly intervals for a six-year period were used to assess changes in channel stability that recorded a cyclic build up of debris and a periodic removal. A long-term monitoring approach is not viable in the majority of research projects due to time constraints. To assess large-scale variations in potential sediment supply and channel stability over these timescales in the Burnhope catchment as part of the rapid assessment approach, comparisons between air photographs of Burnhope Burn in 1951 and 1995 can be made.

Aerial photographs are beneficial in determining the spatial and temporal extent of catchment erosion and have provided a basis for identifying erosion and transport processes in a number of sediment budget studies (Reid, 1981; Reid and Smith, 1992; Reid and Dunne, 1996; Johnson and Warburton, 2002). A comparison between aerial photographs taken in the autumn of 1951 and 1995 provides valuable information on the relative activity and connectivity of sediment supply and transfer in the lower reaches of Burnhope Burn. Comparison between photographs has identified four areas of interest where distinct changes have occurred in terms of relative activity and stability in the channel and hillslope zones. These two annotated photographs are shown in Figure 5.26 while description and discussion of the changes in potential sediment supply to Burnhope Burn is provided below.

1. In box 1 of the 1951 photograph there is evidence of failure in moorland at the head of an active tributary channel of Burnhope Burn. This shallow failure is a potential source of organic and minerogenic sediment to Burnhope Burn. In the 1995 photograph the area of failure and the tributary channel have completely re-vegetated and are largely un-coupled from the main channel.

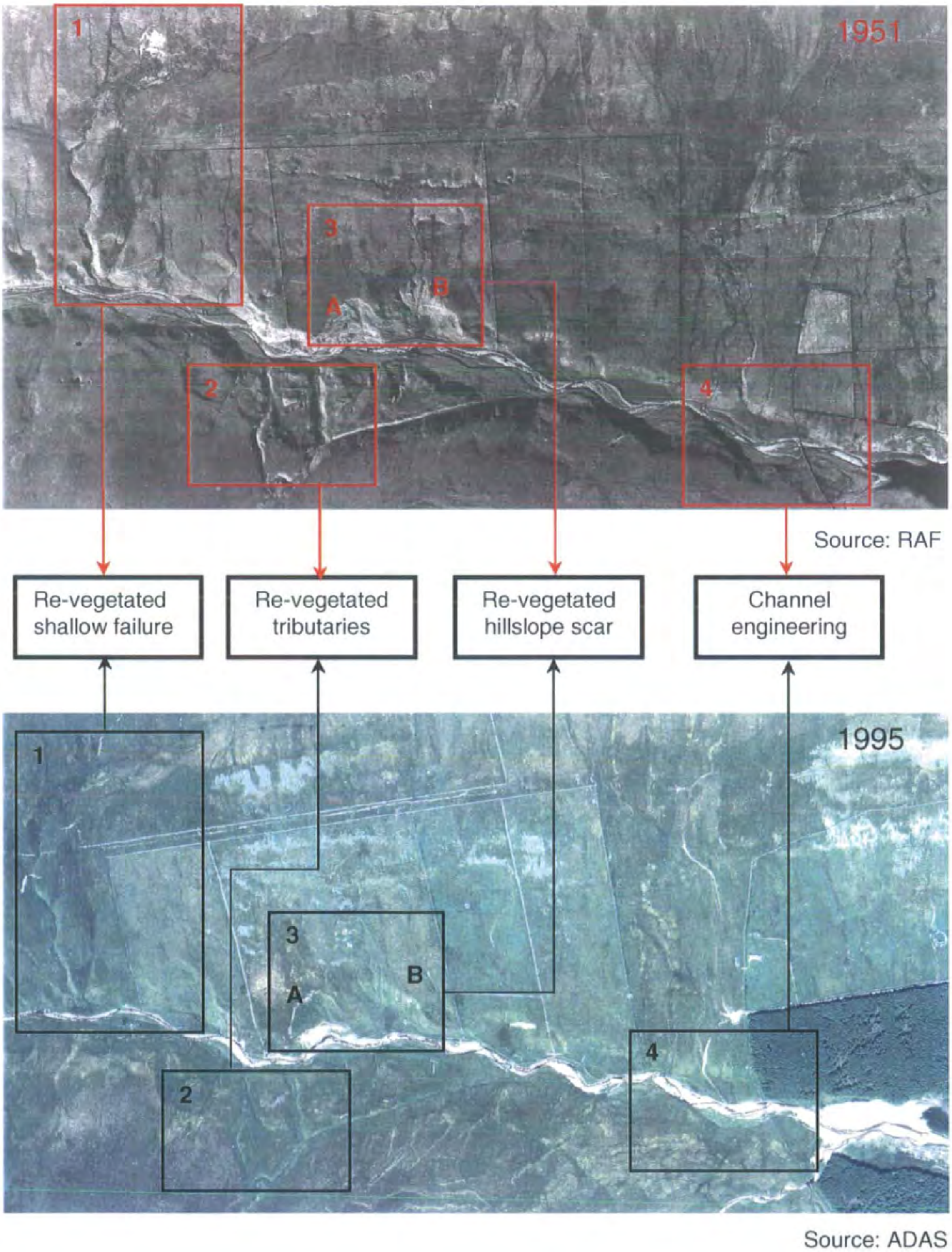
2. The active tributaries highlighted by box 2 on the 1951 photograph are re-vegetated and decoupled from Burnhope Burn in 1995.

3. The stream-side scars in box 3 on the 1951 photograph are two separate features that appear to be connected. These features are labelled A and B for ease of description. Drainage channels are evident above scar B and this surface drainage could have initiated the instability on the slope. In the 1995 photograph these drainage channels and scar B are completely re-vegetated. The head of the scar A is still evident in 1995 and the scar face at the toe of the feature is still active and coupled to the channel. The extent of scar A and the degree of contemporary coupling to the channel is evident from Figure 5.9.

4. The lower reaches of Burnhope Burn in 1951 appear quite confined by stable, vegetated floodplains. In 1995 the active channel is wider with larger expanses of un-vegetated floodplain. This reach has been subjected to extensive reworking by channel engineering that has altered the cross-section of the channel providing potential for in-channel storage of coarse-grained sediment.

There are some difficulties when attempting to compare the 1951 and 1995 photographs. When assessing the black and white photographs it is easier to

Figure 5.26 Air photographs taken of Burnhope Burn in October 1951 and September 1995. The boxed areas highlight features of significant variation in terms of sediment delivery potential through re-vegetation and hillslope/channel connectivity.



distinguish between the morphological features as the surface is not confused by differing shades of colour. The texture of the photographs also differ making it harder to determine gravel deposits in the active channel from the floodplains on the 1951 photograph. The extent of the active channel is clearly visible due to Burnhope Burn being at low flow in the 1995 photograph.

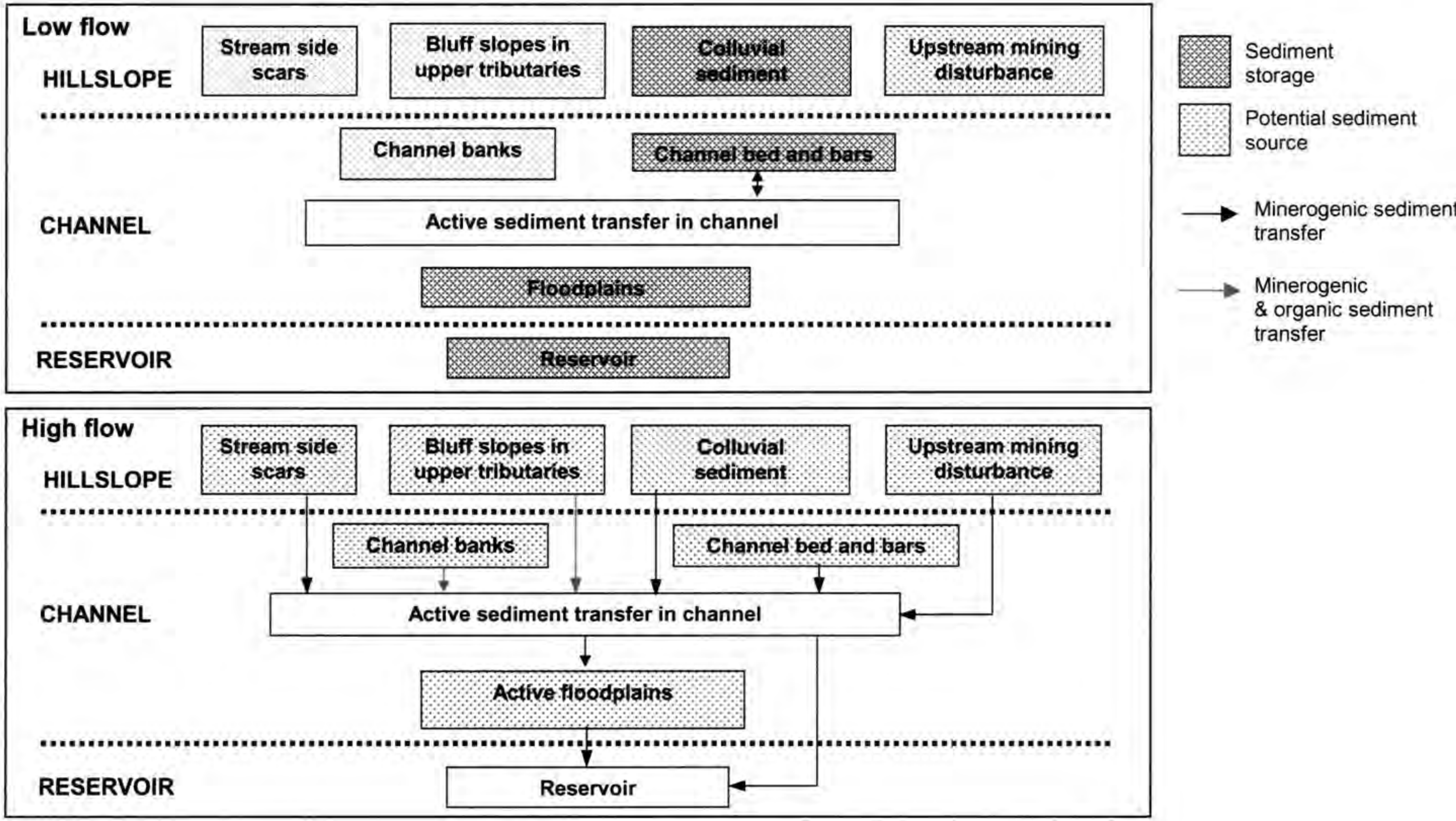
Climate and lithology are the controlling factors on vegetation growth and as lithology is largely the consistent variable it is likely that climate has been the controlling variable on re-vegetation. Figure 5.23 showed that there was generally above-average rainfall for the period 1947 to 1955, recording some of the highest mean annual totals in the series. This could explain the activity of sediment sources and drainage channels and the presence of the shallow failure evident in the 1951 photograph. From the mid 1950s to 1970 the five-year moving average trend shows average rainfall and this is followed by a decade of below average rainfall totals. This period of lower rainfall could have lead to stability in ephemeral drainage channels and promoted vegetation growth on exposed sediment surfaces not inundated by stream flow. Since the early 1980s the trend has been of steadily increasing rainfall until 1996 but it was not until the mid-1990s that rainfall levels reached those experienced in the late 1940s and early 1950s.

It can therefore be concluded that despite the problems of comparison between photographs, the overall evidence suggests that the hillslopes of Burnhope Burn have stabilised over time. Re-vegetation of tributary streams and active scar faces has resulted in an overall decrease in hillslope/channel coupling and therefore a reduction in sediment delivery potential between sources and the channel. From these photographs and field observation there is no evidence of activation of new stream-side scar features but this general trend can not be extended to incised channel banks or small erosion features as these are not clearly visible from aerial photography. Similar trends in re-vegetation of gully systems in peat moorland and tributary streams at Moor House in upper Teesdale have been recorded by Clement (2001) and Higgitt *et al.* (2001) over the same time periods.

5.8 Pathways of sediment transfer

Figure 5.27 is a conceptual model and summary of sediment transfer pathways for both minerogenic and organic sediments at low and high flow magnitudes in the Burnhope and Langtae systems. It identifies the links between sediment source and storage zones highlighted in Figure 5.1. Results from the sediment sourcing section of this

Figure 5.27 Conceptual model of sediment transfer pathways for minerogenic and organic material during low and high flow regimes in terms of sediment preparation, storage during low flow and potential sources of sediment during high flow.



chapter have shown that the majority of stream-side scars are located in first order channels. Over 80% of stream-side scars are located in the upper 50% of the Burnhope catchment. Similar results were found in the Langtae catchment although a higher concentration of scars were located in Langtae Burn which is probably linked to Langtae Burn being more confined in its lower reaches than Burnhope Burn. Overall, surface area of scars in the Burnhope system was twice that measured in Langtae. Also scar surface areas were greater in the larger catchment with over 30% of scars with surface areas greater than 100 m^2 compared to 4% in the Langtae catchment. There were a similar number of scars identified in both catchments which implies that channels in the Langtae system impinge on the valley side slopes more often in the smaller more confined catchment. The connectivity between exposed sediments in stream-side scars and the channel is three times greater in the tributary streams than in Burnhope Burn and scars with the greatest surface area are located in the first order streams. This suggests that the sediment supply is connected in the headwater streams of the system.

Cut banks are also locally important sediment sources that provide predominantly minerogenic sediments with organic materials sourced from the head of the tributary streams. The majority of fine sediment is sourced from exposed scar faces through surface wash and locally through bank failure via undercutting and slumping. The fine matrix of solifluction material along incised channel margins provides potential sources. During low flow there is little sediment transfer evident and exposed sediments from hillslope sources remain uncoupled with the channel (Figure 5.27). During moderate to high flows, slope channel coupling activates potential sediment sources and stores with bluff slopes and cut banks at the head of the tributary streams supplying organic sediments to the system. Coarse-grained sediments are supplied through erosion of exposed bedrock reaches and channel banks composed of solifluction material during high magnitude flows (Figure 5.27).

The dating of flood deposits has provided information on the temporal scales of sediment transfer in the Burnhope and Langtae systems. Tentative connections between rainfall records and the chronology of coarse-grained sediment in both catchments have been made. The majority of deposits were dated within the last twenty years in the Langtae catchment and in the last 100 years in the Burnhope catchment. Variations have been attributed to reworking of older deposits in the confined first order channels of the Langtae system, re-vegetation of older deposits above contemporary channel margins and the use of a multi-species lichenometric approach in the Langtae system. During high flow the movement of coarse-grained sediment freshly supplied from channel banks or reworked boulder toes at the foot of stream-side scars is transferred together with finer sediment fractions. There is evidence of coarse-grained sediment storage throughout the stream network and the ultimate sink of fine sediments from these catchments is likely to be Burnhope Reservoir. In the lowest reaches of Burnhope Burn, at the inlet to the reservoir there is a notable rapid fining of sediments from boulders to gravel then to fine sands as the gradient of the channel decreases. This zone of rapid transition separates the boulder and bedrock bed channels of the upper tributary streams and upper reaches of Burnhope and Langtae Burn from the fine sediment sink in Burnhope Reservoir.

This chapter has provided a spatial and temporal assessment of the sediment transfer system of Burnhope and Langtae catchments by developing a sub-system sediment budget that highlights both coarse and fine sediment supply to the channel. However mapping and observation alone are insufficient for assessing sediment transfer on event timescales. Quantifying sediment yields and monitoring patterns of sediment transport is the next step in establishing a catchment based temporal framework of sediment transfer and this is addressed in the following chapter.

CHAPTER 6 - CATCHMENT SUSPENDED SEDIMENT YIELDS FROM STREAM MONITORING

6.1 Introduction

There are numerous methods of estimating catchment sediment yields ranging from reconstruction of sediment stores in lakes and reservoirs to monitoring rates of on-site erosion. An alternative method is determining yields from monitoring suspended sediment concentration and discharge in stream systems. Monitoring provides a basis for quantitative stream sediment load estimation and is a useful qualitative tool, providing insight into patterns of sediment transfer through variations in sediment supply and flow magnitude.

This chapter discusses the most comprehensive dataset of suspended sediment concentration and discharge measurements currently available for a North Pennine catchment. This dataset is used to investigate temporal scales of sediment transfer on seasonal timescales in the Burnhope and Langtae systems and over event-based timescales in the Burnhope system. Sediment yields are estimated for the study year in both catchments and predicted loads are compared to actual loads for individual storm events. The chapter is in two parts: the first evaluates the sediment rating curve method for estimating catchment sediment loads from May 2000 to February 2001 in the Burnhope and July to December 2001 in the Langtae system. The inaccuracies of this yield estimation method are addressed and the spatial differences in the form of the fitted rating curves are related to sediment transfer regimes in these upland catchments. Seasonal patterns in suspended sediment concentrations are identified and tested using Fourier series analysis. The second part investigates stream sediment dynamics on an individual storm event basis assessing both the patterns of sediment movement on an intra- and inter-storm event basis and total sediment loads over large spatial (catchment) and small temporal (storm event) scales.

6.2 Estimating catchment suspended sediment loads using the 'rating curve' approach

6.2.1 Sediment rating curves and their application

Attempting to predict sediment loads from a quasi-continuous series of discharge measurements involves the use of load estimation procedures to interpolate or extrapolate the data. *Interpolation* procedures assume that suspended sediment concentrations measured at a given point in time are representative of those concentrations during the inter-sampling period (Phillips *et al.*, 1999). Using this procedure alone can be problematic when dealing with data from small drainage basins due to temporal variations in suspended sediment supply. *Extrapolation* procedures involve the development of rating relationships between suspended sediment concentrations and corresponding discharge values. These can then be applied to a continuous record of discharge collected over an extended period to estimate sediment concentrations for that period. The most commonly used extrapolation procedure for estimating sediment concentrations from stream discharge values is the log-transformed least squares regression sediment-rating curve (Fenn *et al.*, 1985; Ferguson, 1986; Phillips *et al.*, 1999). The relationship between suspended sediment concentration and discharge is of the form:

$$C = aQ^b \qquad \text{(Equation 6.1)}$$

where C is the estimated suspended sediment concentration, Q is discharge associated with C and a & b are regression coefficients.

6.2.1.1 Issues of inaccuracy in load estimation; the use of correction factors

Studies using log-transformed least squares regression rating relationships to estimate sediment loads report variable results. Forecasts from the 1981 rating models for the prediction of suspended sediment concentration in pro-glacial streams in Valais, Switzerland recorded underestimation, with uncorrected concentrations representing only 79% of the actual load (Fenn *et al.*, 1985). Walling & Webb (1981a) presented load estimates from the river Creedy in Devon, U.K that were only 20% of the true load. Research by Ferguson (1987) concluded that using the log-transformed rating curve approach results in the underestimation of sediment loads of up to 50%.

These underestimated loads and inaccuracies in predicting suspended sediment concentrations are the result of the statistical method used to fit the sediment-rating curve and the scatter about the regression line. In order to correct for this underestimation, or bias that results from applying the log-transformed least squares regression model, a number of correction factors (CF) can be applied to the calculated loads. Ferguson (1987) proposed the following parametric algorithm:

$$CF = \exp(2.65\, S^2) \qquad \text{(Equation 6.2)}$$

where S^2 is the mean square error of the log-transformed regression. This algorithm attempts to correct for the scatter about the regression line. However, the inherent scatter is also a result of variations in sediment supply and the seasonal effects of sediment availability that cannot be corrected for by this model. Bias increases with the amount of scatter and is positively related to mean square error and load underestimation. As a result, correction factors increase with increasing bias to correct load predictions for underestimation (Ferguson, 1986). Applicability of a correction factor is based on two assumptions firstly that the residuals of suspended sediment concentration are log-normally distributed and secondly that suspended sediment concentration is a power function of discharge.

A similar type of bias correction factor is based on the Smearing estimate. This is a nonparametric retransformation method used to correct for underestimation after fitting a linear regression model to a log scale (Duan, 1983). The Smearing estimate is based on the equal occurrence of residuals and works by 'smearing' their magnitudes in the original units across the range of discharge (Helsel & Hirsch, 1992). The smearing is done by re-expressing the residuals from the log-log equation, then transferring them to the original units and computing their mean (Helsel & Hirsch, 1992). This mean is the bias correction factor and therefore it is not necessary for the data to be log normally distributed for its application. The algorithm is as follows:

$$CF = \left(\frac{1}{n}\right)\sum_{i=1}^{n} 10^{e_i} \qquad \text{(Equation 6.3)}$$

$$e_i = \log(C_i) - \log(C_{ei}) \qquad \text{(Equation 6.4)}$$

where:

$\log(C_i)$ = log of concentration

$\log(C_{ei})$ = estimated log value of concentration for the same observation derived from discharge

n = number of observations (from Phillips *et al.*, 1999)

Hansen & Bray (1987) state that if the concentration residuals are log-normally distributed then the values of both Smearing estimate and Ferguson correction factors will be the same. In a study of suspended sediment yields for the Kennebecasis River in New Brunswick Canada, Hansen & Bray (1987) applied the Smearing correction factor and found the estimates to be within 10% of published sediment survey results. In the present study, both Smearing and Ferguson correction factors are applied where appropriate. Applying both correction factors helps to highlight any deviations from a log normal distribution of suspended sediment concentration residuals and provides a comparison of the bias correction procedures.

Walling & Webb (1988) comment on both the uncertainties and merits of estimating sediment loads using correction factors and report a low level of accuracy and precision in load estimations using the rating curve approach, even after application of correction factors. To investigate the uncertainty of applying correction factors, Walling and Webb (1988) analysed a number of continuous records of suspended sediment concentration and discharge for three rivers in Devon. From the records, actual loads were calculated and compared to those estimated using the rating curve and bias-corrected rating curve approach. The results suggested that bias associated with logarithmic transformation is not the prime cause of the inaccuracy of rating curve estimates of sediment load. Other factors that were not accounted for by correction factors were of importance. These included the seasonal differentiation of the rating relationships and sediment dynamics during storm events, the effects of sediment exhaustion and hysteresis (Walling and Webb, 1988). For Burnhope and Langtae these factors are investigated by examining the accuracy and precision of rating relationships.

6.2.1.2 Accuracy and Precision

Precision is the degree to which load estimations from sets of data recorded at the same sampling frequency differ. It is concerned with the dispersal of these load estimations and reflects the degree of random error (Phillips *et al.*, 1999). Precision is likely to be affected by external forces influencing sediment supply such as sediment preparation, frost action and sediment exhaustion. Changes in sediment supply as a result of rainfall magnitude and frequency influences the amount of sediment transported. This really limits the value of rating curves as an extrapolation method and highlights the requirement of high frequency sampling in order to increase the level of precision. Ferguson (1987) stated that more intensive sampling schemes had a higher correlation and recorded a lower value of underestimation.

The accuracy of load estimation is related to bias. Bias indicates the degree of systematic error within the procedure and is calculated from the difference between actual loads and measures of central tendency of estimated loads (Phillips *et al.*, 1999). For more accurate sediment loads predictions, correction factors are applied as described above to remove bias from the data sets. Bias increases with the amount of scatter about the regression curve and is positively related to standard error and load underestimation (Equation 6.2). As a result there is a negative relationship between accuracy and precision.

Drainage basin scale is also an important determinant when considering accuracy and precision of load estimates. Walling & Webb (1988) found that the degree of underestimation of sediment loads decreased with increasing basin size. This could be because the larger basin systems tend to have smoother discharge and sediment concentration relationships and the larger basins tend to buffer the effects of low-frequency, high-magnitude events. This could result in reducing the scatter about the regression line creating a more accurate measure of suspended sediment yield with lower bias-correction factors. Considerations of spatial scale play an important role in explanations of specific sediment yield (De Boer and Crosby, 1996); however, the relationship between specific basin yields and basin scale is complex. De Boer and Crosby (1996) state this is due to yields and specific yields of suspended sediment being controlled by supply conditions as opposed to transport capacity that does not increase uniformly with basin scale. For these reasons, both specific and total suspended sediment yields will be quoted for Langtae and Burnhope catchments.

6.3 Periods of data collection and least squares regression analysis of data from the Burnhope and Langtae systems

6.3.1 Data collection

This section describes the sampling strategy used to generate suspended sediment concentration data. The monitoring periods for the suspended sediment concentration and discharge measurements for Burnhope and Langtae are shown in Figure 6.1. Shaded boxes denote the periods of sampling and variations in the shading refer to the sub-sampling of the full data-sets described in section 6.3.3. Quasi-continuous water sampling was carried out at Burnhope and Langtae with additional event-based sampling at Burnhope. Suspended sediment concentration monitoring at Langtae was carried out over a six-month period (July 2000 to December 2000) at six hourly intervals and at Burnhope for ten months (May 2000 to March 2001) at the same frequency. In addition, event-based storm sampling was carried out at Burnhope at fifteen-minute intervals (October & November 2000) and at five- to ten minute intervals (January to March 2001). Discharges were determined from stage records calibrated using point velocity-area flow measurement. Table 6.1A and B provide a summary of descriptive statistics for suspended sediment concentration and discharge data from the Burnhope and Langtae catchments. Maximum suspended sediment concentrations of 389 and 125 mg l^{-1} and maximum discharges of 4.32 and 2.03 m^3s^{-1} were recorded over the monitoring periods for the Burnhope and Langtae catchments respectively. To estimate suspended sediment yields for known discharges recorded at 15-minute intervals over the monitoring period, extrapolation procedures (rating curves) were used to create a rating relationship between stream discharge and suspended sediment concentration.

6.3.2 Application of least squares regression to data sets from Burnhope and Langtae

The relationship between suspended sediment concentration and discharge for the whole monitoring period for each of the two catchments was determined using least squares regression (Equation 6.1). Figure 6.2 is a least squared regression scatterplot of suspended sediment concentration against discharge for all observations in the Burnhope and Langtae data sets. Figure 6.2A show the relationship for the Burnhope data set is non-linear with a degree of curvature with increasing discharge. There is also a problem of non-constant variance or heteroscedasticity in the data, as the variability in suspended sediment concentration appears to increase with discharge.

Figure 6.1 Timeline of suspended sediment and discharge monitoring for Langtae and Burnhope systems.

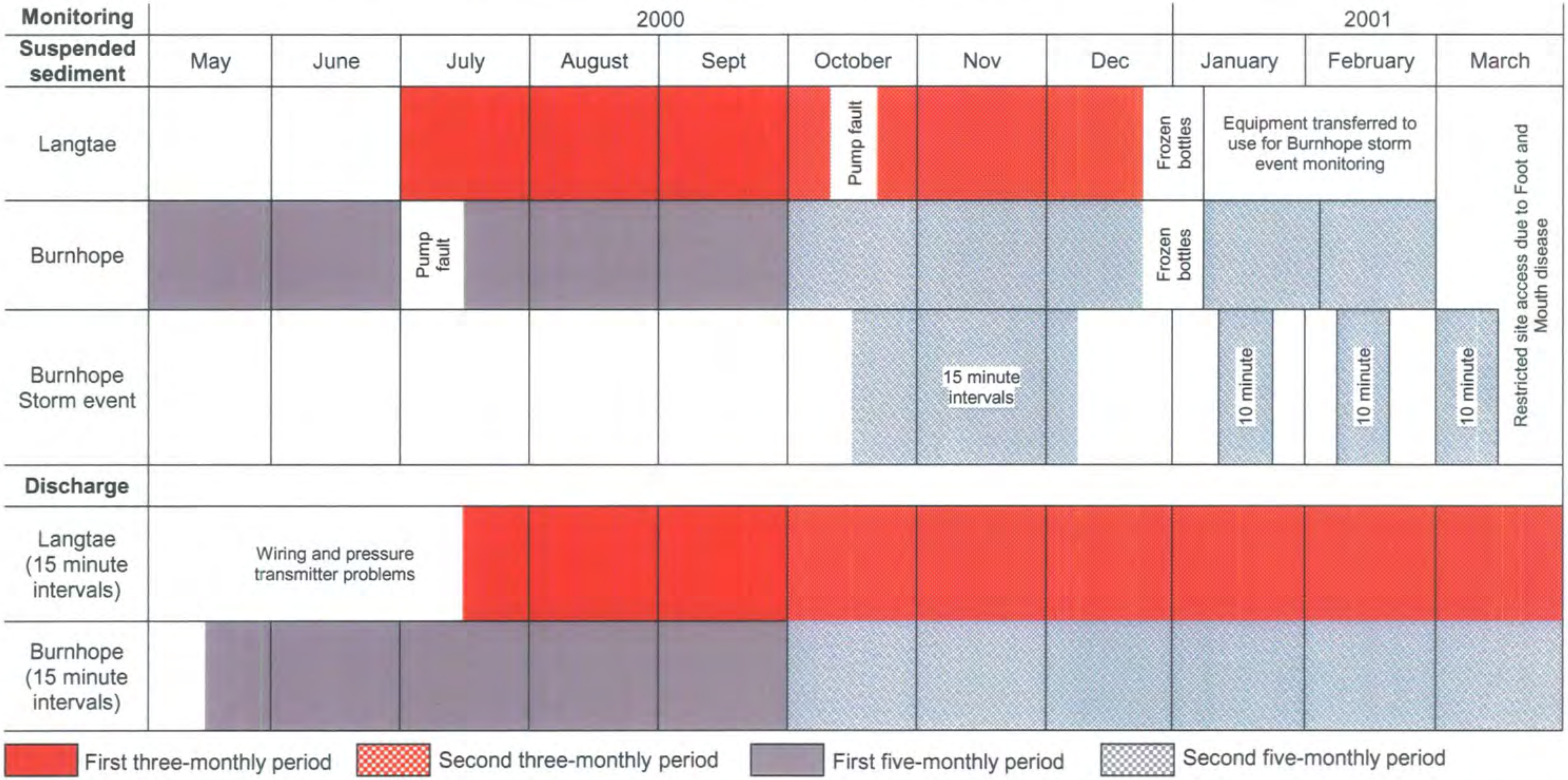


Table 6.1 Descriptive statistics for suspended sediment concentrations and discharge for the (A) Burnhope and (B) Langtae datasets.

(A)

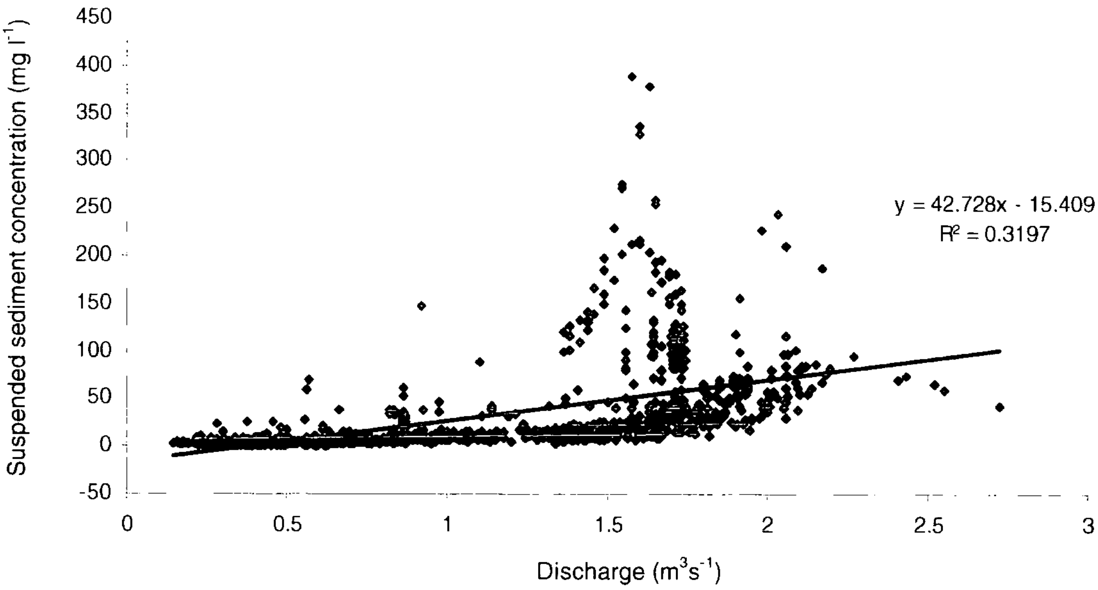
Descriptive parameter	Suspended sediment concentration (mg l^{-1})	Discharge (m^3s^{-1})
Mean	29.01	1.04
Standard Error	1.32	0.02
Median	9.84	0.92
Standard Deviation	45.82	0.61
Range	388.95	2.58
Minimum	0.16	2.03
Maximum	389.11	4.30
Count	1203	1203

(B)

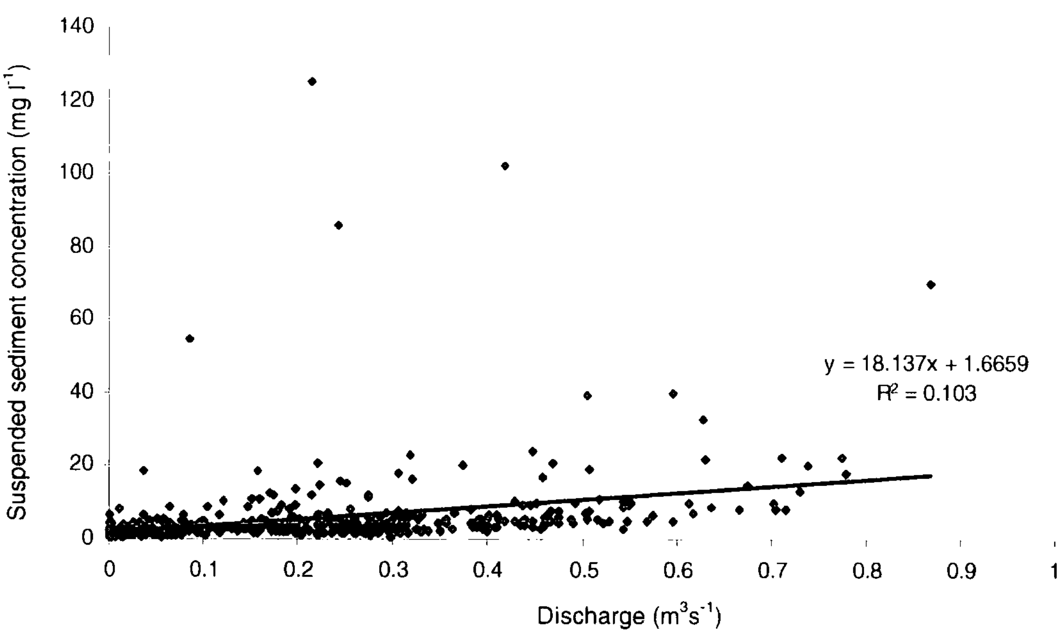
Descriptive parameter	Suspended sediment concentration (mg l^{-1})	Discharge (m^3s^{-1})
Mean	5.50	0.21
Standard Error	0.48	0.01
Median	3.17	0.19
Standard Deviation	10.24	0.18
Range	124.77	0.87
Minimum	0.31	0.00
Maximum	125.08	0.87
Count	458	458

Figure 6.2 Ordinary least squared regression rating curves for the (A) Burnhope and (B) Langtae systems.

(A)



(B)



This is also the case in Figure 6.2B with extremes of suspended sediment concentration in the Langtae system increasing with discharge. To solve this problem some type of transformation of both variables is required. Figure 6.3A and B show the results of nine histograms of transforms for the Burnhope data set according to the 'ladder of powers' and compares the normality of the transformations for suspended sediment concentration and discharge respectively. These histograms are useful for selecting the most normally distributed transformed variable only and not for inferring the most robust transformation for the regression model. From Figure 6.3A it is clear that a log-transformation of suspended sediment concentration is closest to a normal distribution, but for discharge in Figure 6.3B the choice is not so obvious. The square root and log-transformations are the closest to a normal distribution, but the log-transformation of discharge was chosen for developing the regression model due to the square root transformation producing negative regression coefficients. Figure 6.4A and B show the log-transformed rating curves for the full data sets for Langtae and Burnhope catchments. These general rating relationships include all monitored suspended sediment and discharge data collected throughout the monitoring period from both catchments. Generally, the form of the fitted model has improved for both systems. Problems of non-consistent variance have been accounted for and the R^2 values improved using this transformation.

For each of the rating curves derived for Burnhope and Langtae, plots of the residuals of concentration were produced to test for a log-normal distribution. Figure 6.5 shows three residual plots that are commonly used to check the quality of the regression model. These plots are based on the full Burnhope data set. Under ideal circumstances, plots A and B would not show any systematic structure in the residuals. This is the case for both plots with an approximately equal weighting of points above and below the reference line plotted at zero. This is indicative of a regression model that fits the data well. Figure 6.5C is a normal probability plot, which is a graphical technique for assessing whether or not a data set is approximately normally distributed (Chambers *et al*, 1983). The data are plotted against a theoretical normal distribution, which is a straight line. The plot shows that the majority of points lie along this line and therefore the model fits the data set. The same procedure was carried out for the Langtae dataset and for Burnhope and Langtae the general curves met these assumptions so the bias could be corrected.

Figure 6.6 shows the comparison between Langtae and Burnhope general regression models. The Langtae system has a gently sloping trend line in comparison to the steeply sloped line from the Burnhope system. In comparison to the Burnhope system,

Figure 6.3 Histograms based on different transformation methods used to identify the most robust method of transforming the variables of (A) suspended sediment concentration (mg l^{-1}) and (B) discharge (m^3 s^{-1}).

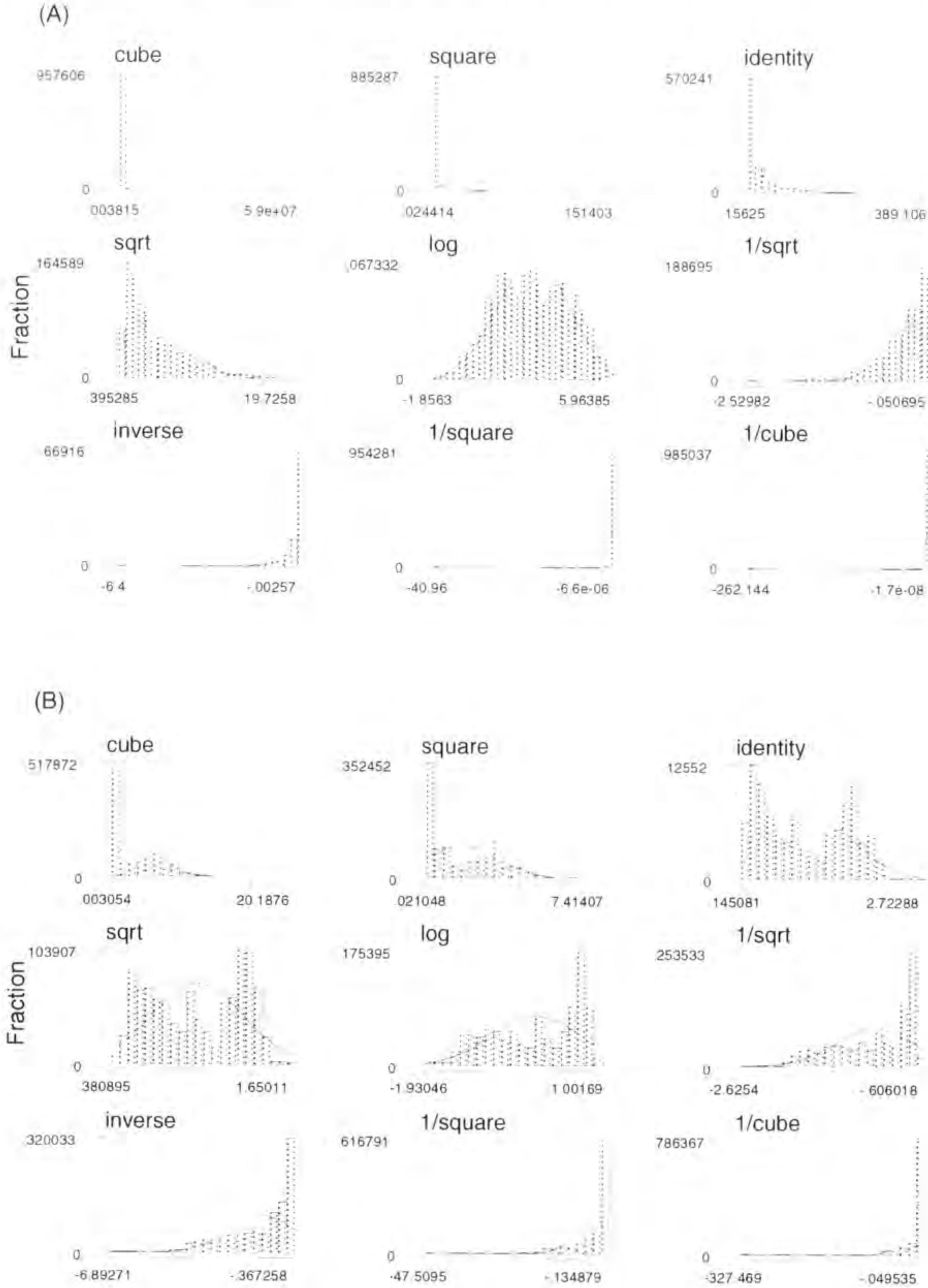
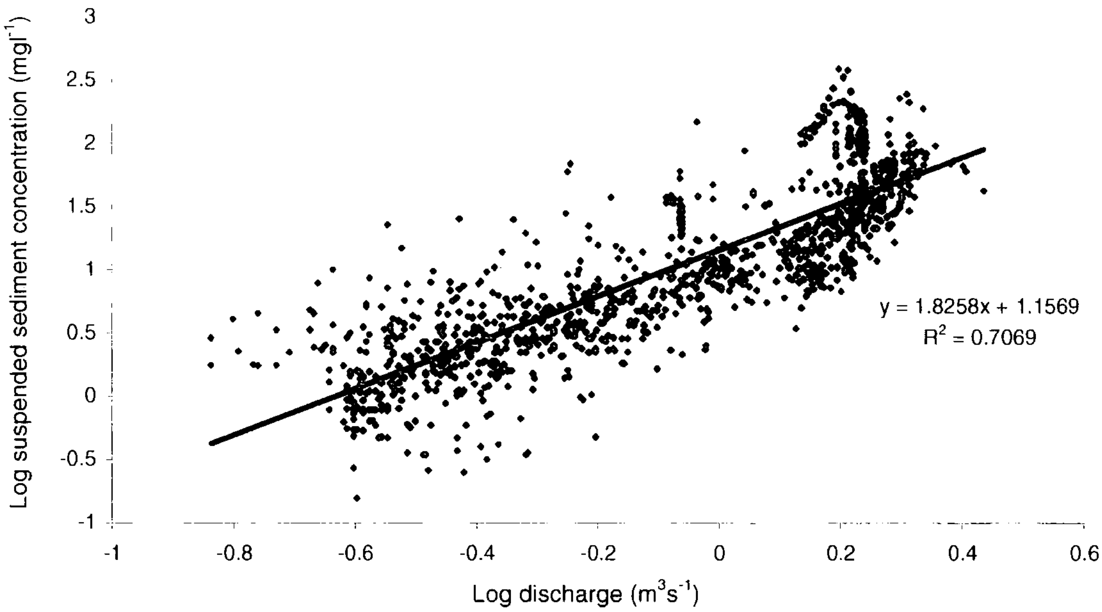


Figure 6.4 General transformed rating curves for the (A) Burnhope and (B) Langtae systems.

(A)



(B)

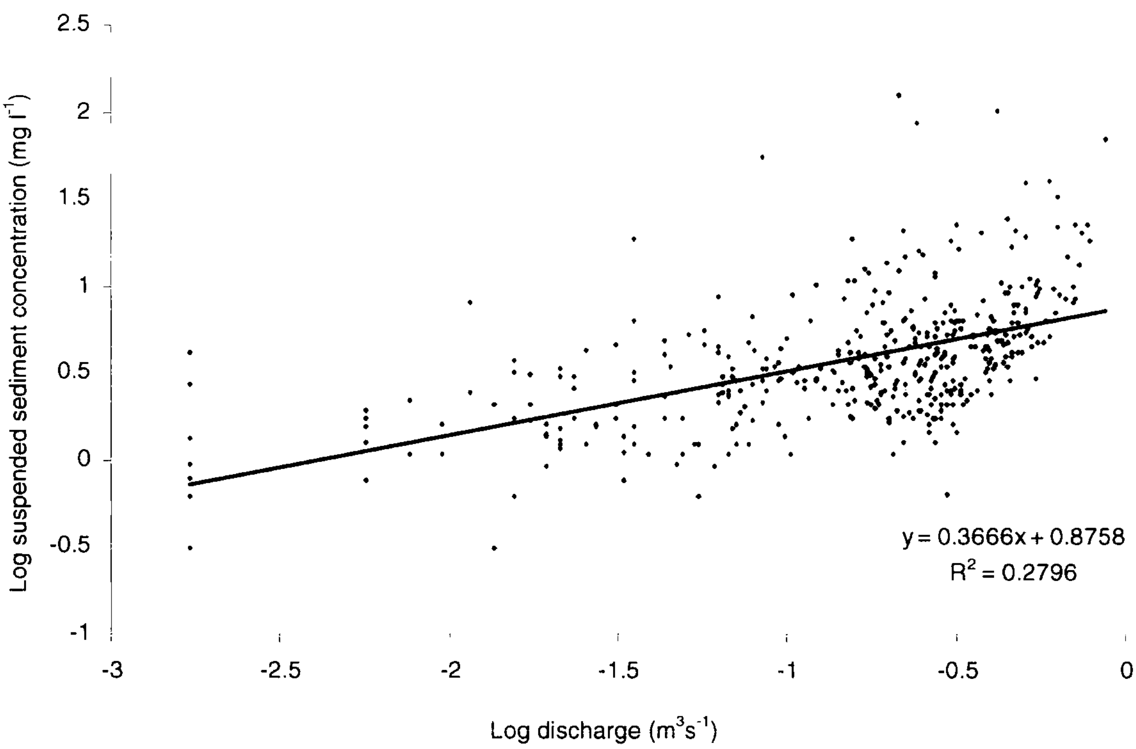


Figure 6.5 Plots of suspended sediment concentration residuals from the Burnhope data set against (A) predicted (B) time and (C) the normality of residuals.

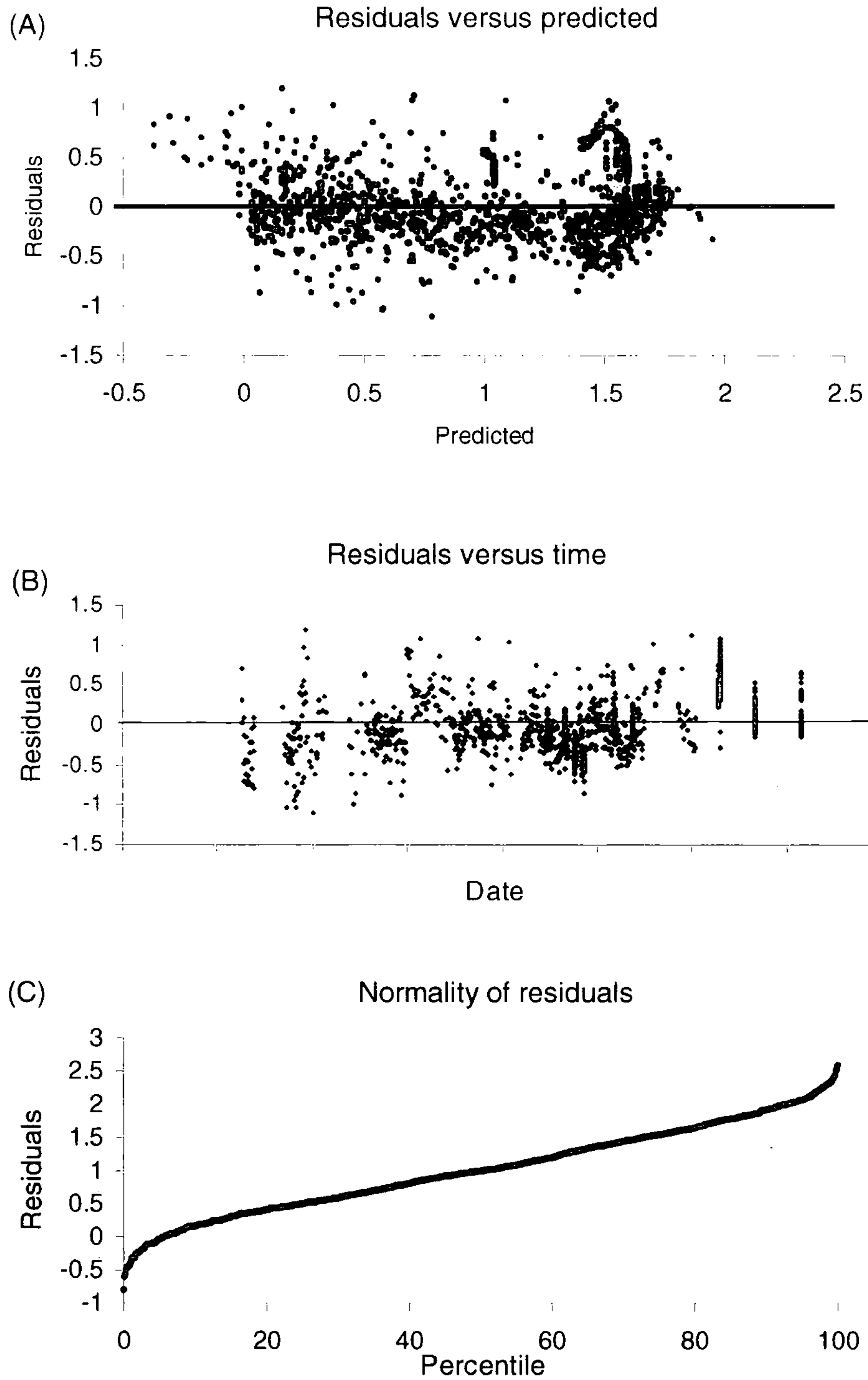
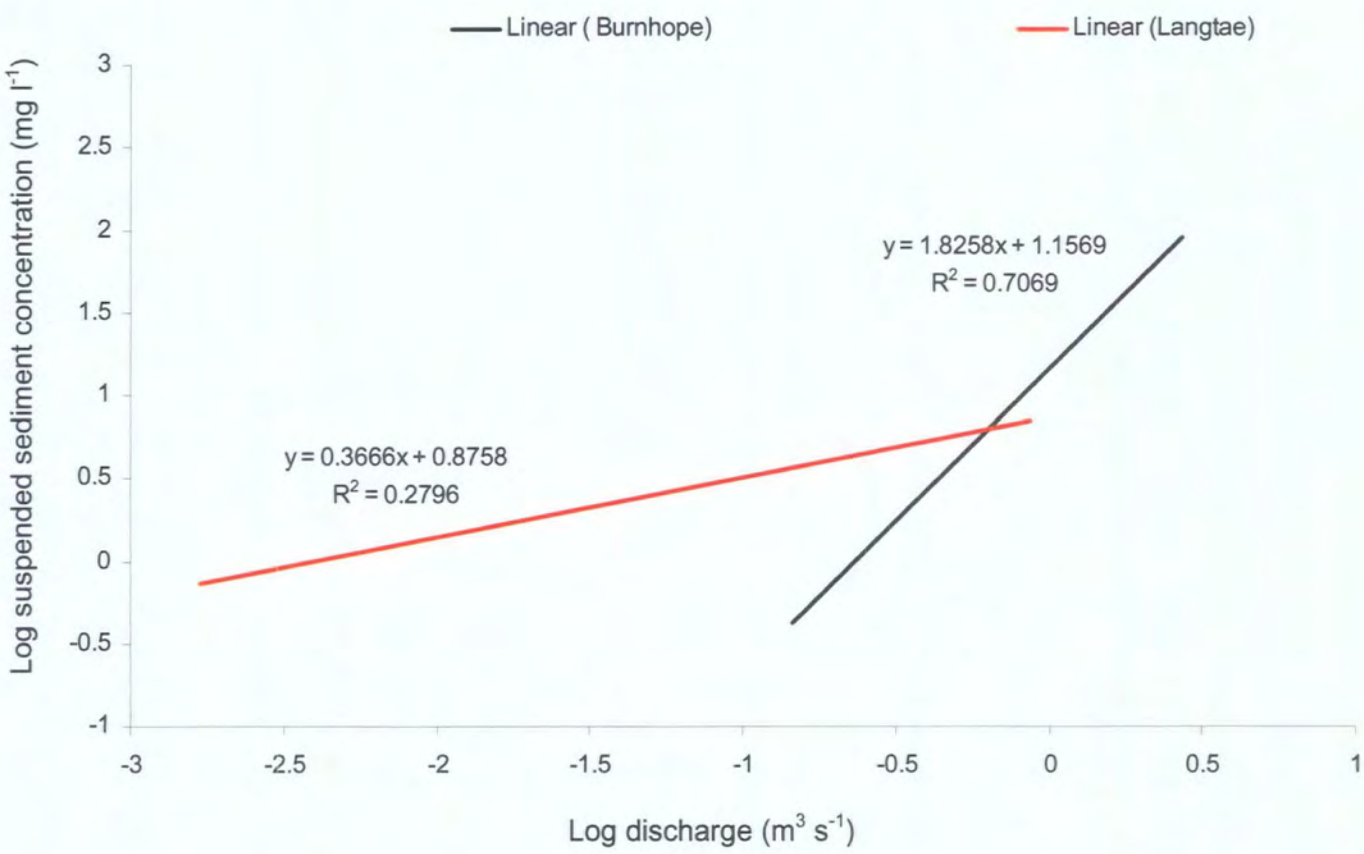


Figure 6.6 General rating curves for the Burnhope and Langtae systems.



sediment concentrations are higher at lower discharges in the Langtae system. The opposite is true during high-discharge events when suspended sediment concentrations are greater in the Burnhope system. When considering the drainage basin characteristics of the two systems, the smaller Langtae system has steeper channel gradients and greater connectivity between sediment sources and the channel during low flow conditions (Chapter 5, Section 5.3). For this reason, sediment transfer will occur at lower discharges in the smaller system. In the larger Burnhope system, sediment sources remain uncoupled during low discharges but once sediment sources are activated during periods of increased discharge, much more sediment is transferred through the system, often resulting in exhaustion of available sediment supply (Chapter 5, Section 5.3). Higher discharges are recorded in the Burnhope system when the highest sediment concentrations are recorded. In summary, sediment transfer in the Burnhope system occurs at a higher discharge threshold but the concentration of sediment transferred at given discharges is greater than in Langtae revealing different levels of connectivity between sediment sources and the channel in smaller and larger systems. Relating to the results in Chapter 5, there are a greater number of potential sources (cut banks and stream-side scars) in the Langtae system per unit stream length, which supports this argument.

6.3.3 Sub-sampling the Burnhope and Langtae data sets

The data series from both catchments were divided into two equal periods, five-monthly periods for Burnhope and three monthly periods for Langtae (see Figure 6.1) and into seasons. Dividing the data set into portions in such a fashion aids investigation into the variations in strength of regression when the data set is split and to identify any seasonal trends that may exist in the data set. By developing different rating curves for each sub-sampled data set, the accuracy of the predicted sediment loads from each corresponding rating curve can be assessed. The residuals of these rating relationships were examined to ensure they fitted the assumptions of applying correction factors discussed in the previous section. They were log-normally distributed and it was established that concentration was a power function of discharge; therefore, correction factors were applied to account for underestimation.

The data were split into seasons on the basis of the observed hydrological characteristics of the upland catchments and in line with other studies in similar environments. For example, in the Southern Pennines, Labadz (1988) found the months of December, January and February to be the coldest while June, July and August were the warmest. These seasonal divisions are in line with those of the UK Environmental Change Network (ECN) sites at Moor House in upper Teesdale (Burt *et al.*, 1998b). The seasonal temporal splits are as follows:

Spring	(1^{st} March to 31^{st} May)
Summer	(1^{st} June to 31^{st} August)
Autumn	(1^{st} September to 30^{th} November)
Winter	(1^{st} December to 28^{th} February)

Each regression equation was applied to the corresponding seasonal period of monitored discharge (Figure 6.1) and summed to provide an overall estimate of suspended sediment yield for the study year. For each seasonal curve from the Burnhope data, the criteria were met for the use of correction factors to account for underestimation bias. The predicted sediment yields for the Burnhope and Langtae systems are shown in Tables 6.2A and B. The same methods have been applied to regression equations generated from five- and three-monthly data sets for Burnhope and Langtae respectively.

For the Langtae dataset, suspended sediment concentration monitoring was carried out between July and December 2000. There are no data for the spring season. For the summer, autumn and winter curves, there were weak relationships between suspended sediment concentrations and discharge and the assumptions were not met for using correction factors. Therefore seasonal rating curves have not been produced for the Langtae system. Only the general rating curve fulfilled the assumptions that suspended sediment concentration was a power function of discharge and residuals of suspended sediment concentration were log-normally distributed for the Langtae system. Further analysis of the form of the regression models for each data set is required through examination of the regression equations. The regression models for Table 6.2A and B are given in Tables 6.3A and B. The next section determines the most viable rating model for sediment yield estimation and will also consider the role of rating curve coefficients in evaluating variations in the sediment transport regimes between catchment systems.

Table 6.2 Predicted sediment yields for the (A) Burnhope and (B) Langtae systems.

(A)

Regression type	Total Yield (t)	% Total yield estimate increase with CF	Specific yield ($t/km^2/10$ months)	Specific yield ($t/km^2/yr$)
General	163.30	*	13.84	16.61
General & Ferguson	229.84	40.7	19.48	23.37
General & Smearing	238.15	45.8	20.18	24.22
4 Seasons	150.25	*	12.73	15.28
4 Seasons & Ferguson	194.30	29.3	16.47	19.76
4 Seasons & Smearing	200.30	33.3	16.97	20.37
2, 5 month periods	138.39	*	11.72	14.07
2, 5 month periods & Ferguson	198.11	43.2	16.79	20.15
2, 5 month periods & Smearing	191.09	38.1	16.19	19.43

(B)

Regression type	Total Yield (t)	% Total yield estimate increase with CF	Specific yield ($t/km^2/8$ months)	Specific ($t/km^2/yr$)
General	22.30	*	7.44	11.15
General & Ferguson	28.79	29.1	9.60	14.40
General & Smearing	31.88	42.9	10.63	15.94

Table 6.3 Regression models for the (A) Burnhope and (B) Langtae systems.

(A)

Criteria for regression	No of cases	Intercept value (*a*)	Slope value (*b*)	R^2	t-value*	Correction factors	
						Ferguson	Smearing
General	1203	1.8258	1.1569	0.71	53.82	1.407	1.458
Seasonal (Spring)	73	2.3380	1.0812	0.76	17.08	1.263	1.408
Seasonal (Summer)	194	0.7341	0.5702	0.06	3.23	1.504	1.681
Seasonal (Autumn)	560	1.4982	1.0163	0.73	38.84	1.188	1.238
Seasonal (Winter)	372	1.9093	1.3757	0.59	23.21	1.348	1.355
1st 5 month period	370	1.1766	0.8277	0.31	13.00	1.374	1.451
2nd 5 month period	833	1.7589	1.1937	0.57	33.23	1.383	1.427

(B)

Criteria for regression	No of cases	Intercept value (*a*)	Slope value (*b*)	R^2	t-value*	Correction factors	
						Ferguson	Smearing
General	410	0.3666	0.8758	0.28	12.58	1.29	1.43

*All values significant at 0.01 significance level (n = >70, t = 2.65)

6.4 Analysis of regression equations for the Burnhope system

Comparing the correlation coefficients for each regression makes it possible to determine which has the strongest linear relationship (Table 6.3A). Generally suspended sediment concentrations increase with discharge. The summer regression explains little variance in suspended sediment concentration with an R^2 value of 0.0631 but the level of variance explained by the remaining seasonal and general models are statistically significant (99% conf.) and therefore justify the use of a bivariate regression model. Pair-wise comparison between seasonal regression lines and the general regression line enables seasonal variations in sediment transfer to be investigated (Table 6.4).

Figure 6.7 shows seasonal rating curves using data sets sub-sampled from the Burnhope data. These figures provide visual representation of the regression equations in Tables 6.3A and 6.4. All the regressions have positive intercept and slope coefficients, with the autumn and spring curves displaying the highest intercepts. The summer curve has the lowest intercept values that are significantly different from the general regression (Table 6.4) implying that the least amount of easily transportable material is available during the summer months. However, with analysis of the slope coefficients, autumn and spring record high *b* coefficients where the summer regression shows lower values. This possibly indicates that during the autumn and spring the threshold discharge capacity for sediment transfer is reached and sediment supply could become the limiting factor. In the summer, the flatter curve (figure 6.7B) is significantly different than the general regression curve (Table 6.4) and indicate that sediment supply and flow competence are both low. An alternative interpretation based on the theory of Walling (1974) is that high *b*-coefficients in the autumn and winter rating models could indicate the availability of new sediment sources. Spring and autumn curves (Figure 6.7A and 6.7C respectively) could be considered the most accurate by recording the lowest correction factors and also having the strongest linear relationship. This could be a result of autumn and spring falling between the extremes of temperature and rainfall experienced during the summer and winter months and hence being less susceptible to the vagaries of sediment supply related to sediment exhaustion in the winter and sediment surges during summer connective rainfall events. However, the winter regression line is significantly different than the general model with higher intercept values that indicates the availability of sediment during the winter is greater, with higher sediment concentrations at lower flow.

Table 6.4 Pair-wise comparison of seasonal regression lines to the general regression.

Regression	Intercept	Standard error	Slope	Standard error
Spring	1.0812	0.0386	**2.3380**	0.1548
Summer	**0.5702**	0.1034	**0.7341**	0.2036
Autumn	1.0163	0.0110	1.4982	0.0385
Winter	**1.3757**	0.0185	1.9093	0.0821
General	1.1569	0.0107	1.8258	0.0339

Bold values are significantly different from the general regression ($P > 0.05$)

Figure 6.7 Rating curves of suspended sediment and discharge data for Burnhope Burn divided into seasons (A) spring (B) summer (C) autumn and (D) winter.

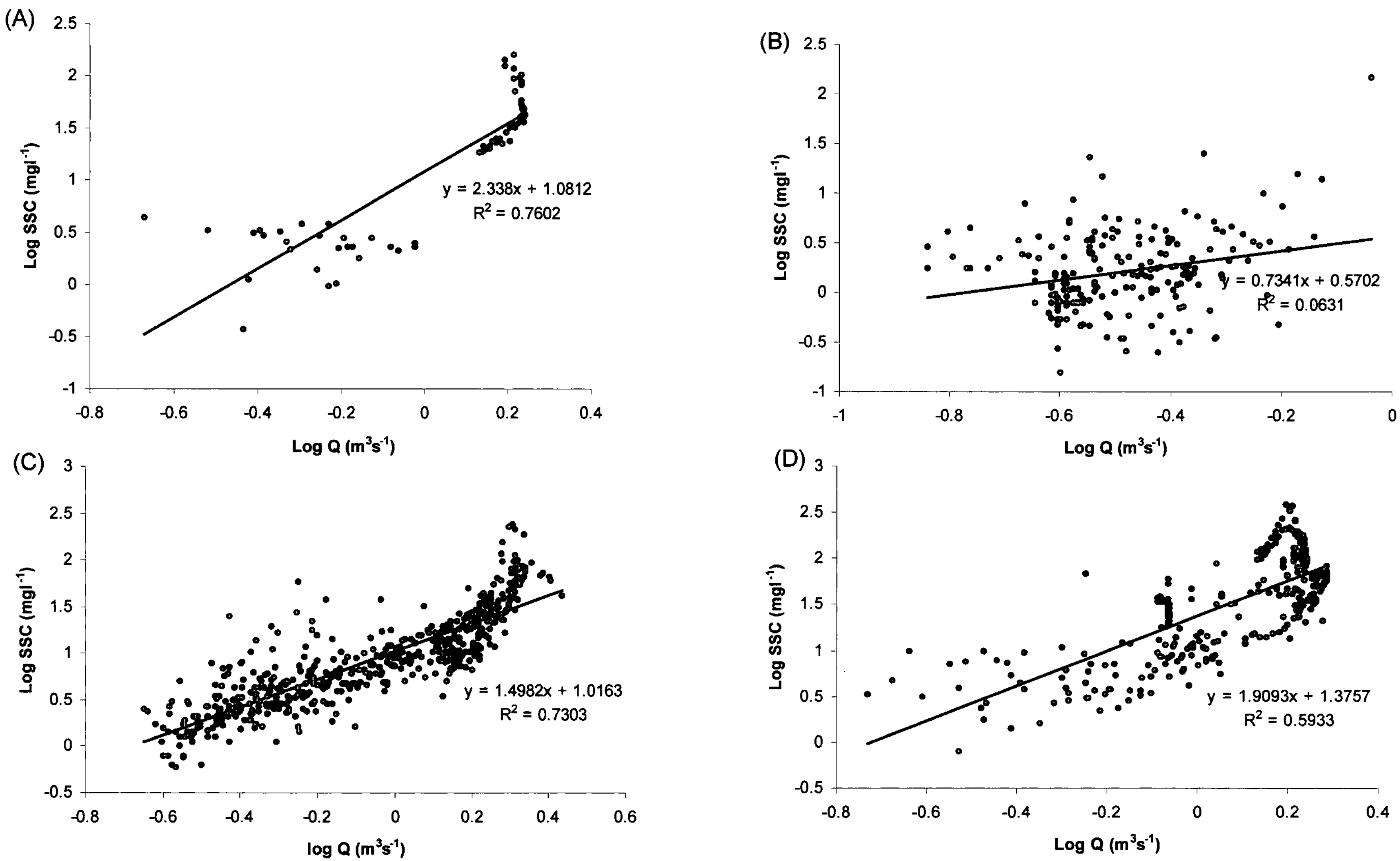
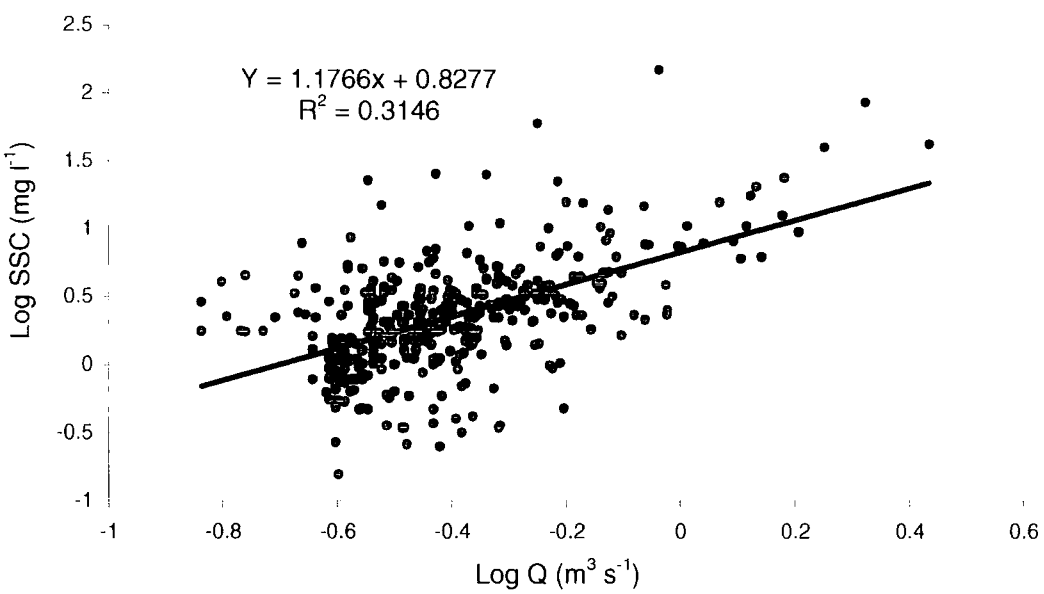


Figure 6.8 shows the rating curves based on the Burnhope data set being split into two, five-monthly periods. These models have weaker linear relationships than the seasonal split. The first period records the lowest correlation coefficients but has 50% fewer observations that could lead to greater inaccuracy. Figure 6.8A shows clustering of points at lower suspended sediment concentrations and discharge readings that could lead to underestimation of concentrations at higher discharges. The second five-monthly period incorporates the storm data as this event monitoring period is restricted to the autumn and winter months. There is clustering of data points at higher discharges (Figure 6.8B). From observation of the relationship between variables on the winter rating curve (Figure 6.7D), the clustering of high sediment concentrations at high discharge could lead to underestimates of concentration at low discharges. The slope coefficient value is the largest and the winter curve is the steepest. The *a* coefficient value indicates that the winter system could be limited by sediment supply. However, during events when pluses of sediment are activated and sediment supply is no longer limited, sediment transport occurs producing the clustering of high sediment concentrations at high discharge evident in Figure 6.7D. This supports the theory of underestimation of concentration at low discharges related to the winter rating curve. These discrepancies are incorporated within the seasonal estimates of total sediment yield as each seasonal curve is applied to relevant discharge data and summed to give total yields for the study year.

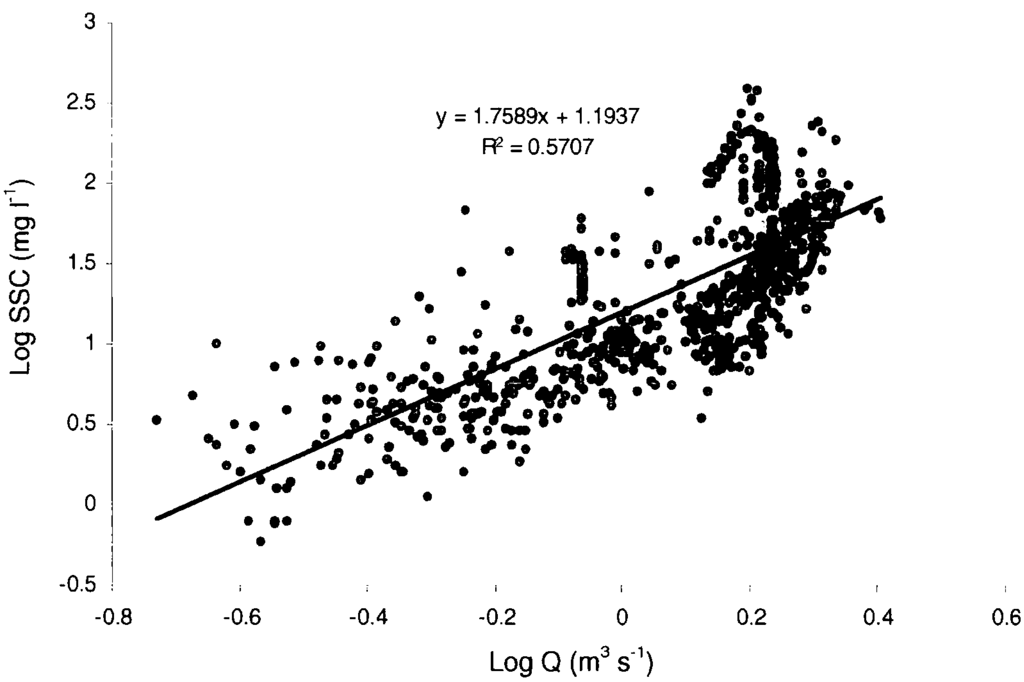
The sediment yields predicted using the general, seasonal and two five-monthly periods have provided uncorrected total load estimates of between 138 and 163 tonnes (Table 6.2A). Once corrected for underestimation bias using both Ferguson and Smearing correction factors, the resulting estimates range between 194 and 233 tonnes. Uncorrected values underestimate corrected sediment loads by between 29 and 45%. As there are no actual loads to compare estimates from each of the rating curves, this poses problems in determining the most suitable rating curve for predicting sediment concentration. From evaluation of the regression equations for each of the three rating relationships, the seasonal curves are likely to be the most appropriate. This is due to the large variability in concentration and discharge relationships between seasons. Each season appears to exhibit different sediment dynamics in response to changes in temperature, precipitation and discharge. The discrepancies in predicting sediment load are reduced if the regression equation from each seasonal curve is applied to relevant periods of monitored discharge. This reduces the effects of inter-seasonal variability, which are not accounted for in the general curve or the first five-monthly split. To this end, the overall estimates of sediment yield from these the general and two five-monthly period split curves should be treated with caution. The

Figure 6.8 Suspended sediment-rating curves for sub-sampled Burnhope data set (A) first five-monthly period and (B) second five-monthly period.

(A)



(B)



seasonal trend in suspended sediment concentration is investigated further in the next section.

6.5 Seasonality in suspended sediment concentration in the Burnhope system

The use of a bivariate model to predict suspended sediment concentration from discharge is restrictive in that it does not account for variations in sediment supply over different seasonal periods. Discharge is dependent on runoff, which in turn is controlled primarily by precipitation. Seasonal variations in precipitation in this study together with variations in sediment supply are inherent in sediment transport regimes and it is appropriate that seasonality in suspended sediment concentration in the Burnhope system has been investigated using seasonal rating curves (Section 6.4). The influence of seasonality on the data set collected from Burnhope can be further explored using Fourier series analysis. This method is based on using oscillating trigonometric functions of sines and cosines as variables (Rayner, 2001). These functions are applied to cyclic patterns in data that are time-variant, for example data that vary seasonally (Davis, 1973). In order to analyse whether there is a seasonal trend in the suspended sediment data set from Burnhope, sine and cosine variables were created on the basis of date and time based on the expected seasonal variations in discharge. The day, month, year and time have been expressed as fractions of a year (FOY) so that January, June and December represent 0, π and 2π radians respectively. The sine variable was calculated as follows:

$$\sin(2\pi \text{ FOY}) \qquad \text{(Equation 6.5)}$$

and the cosine variable;

$$\cos(2\pi \text{ FOY}) \qquad \text{(Equation 6.6)}$$

Multiple regression was conducted incorporating sine, cosine and log discharge (log Q) variables to see if the slope coefficients for the sine and cosine variables were significantly different from zero. The results are shown in Table 6.5.

Table 6.5 Output for multiple regression analysis.

Number of Obs = 628
R-squared = 0.521

Log SSC	Coeff.	Std Err.	t-value	P>|t|	95% Conf. Interval	
Log Q	1.0537	0.6245	16.87	0.000	0.931	1.176
sine	-0.737	0.279	-2.64	0.009	-0.129	-0.019
cosine	0.158	0.021	7.44	0.000	0.116	0.200

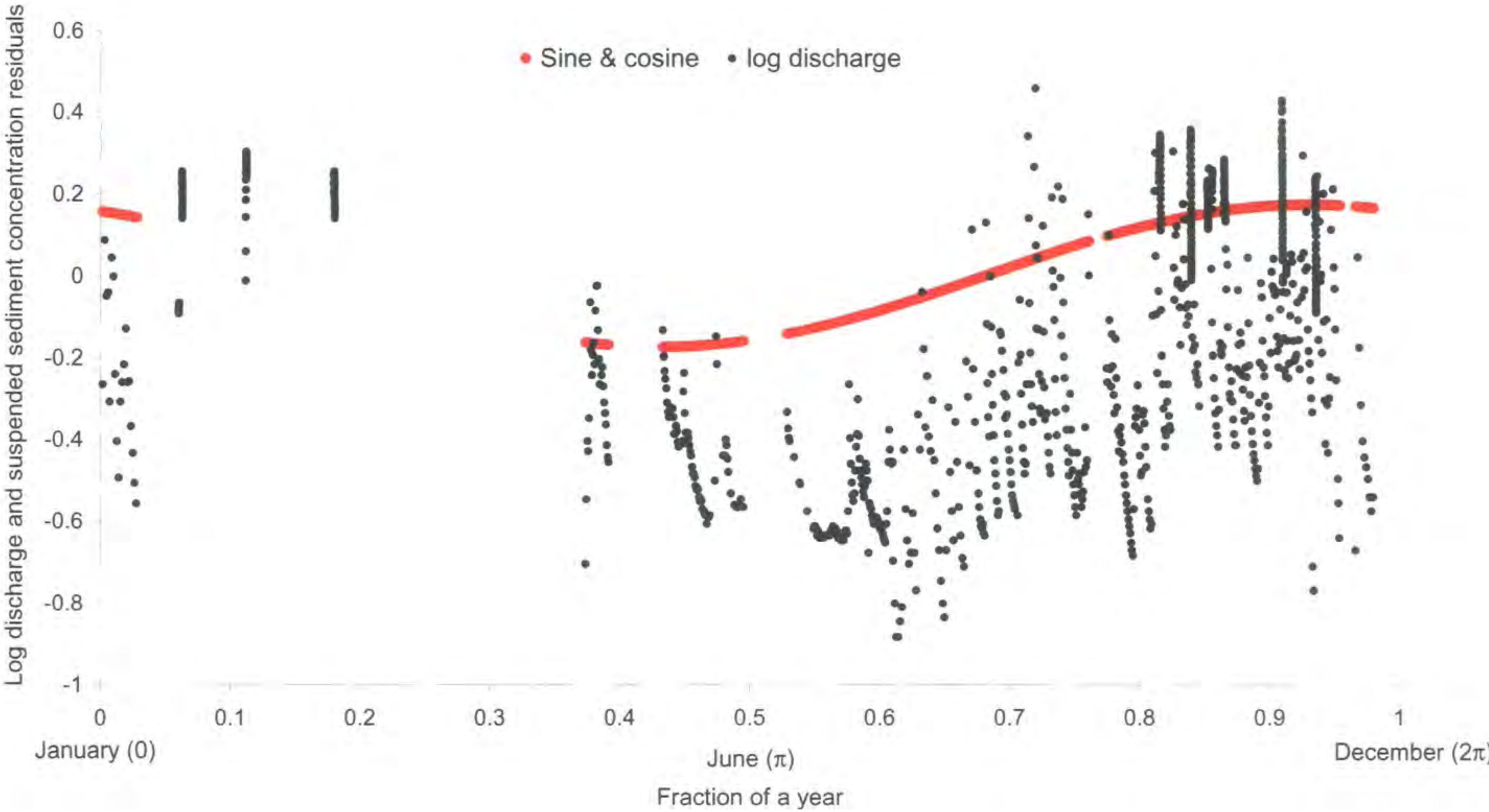
The t-values highlight that the log Q variable is most influential variable but the *p*-values signify the importance of including all three variables in the model. The model takes the form as shown below:

$$\text{Log SSC} = a + b_1 \log Q + (b_2 \sin 2\pi \text{ FOY}) + (b_3 \cos 2\pi \text{ FOY})$$

As shown in the model above, the variables of sine and cosine were amalgamated to produce the model for assessing the influence of seasonal variations. Figure 6.9 shows the results of applying this model to the Burnhope dataset. There appears to be a trend in log Q data that corresponds to the trend of the sine and cosine variable that peaks during the winter months and troughs during early summer. This indicates that there are seasonal variations in the data set. The peak in the sine and cosine variable is recorded on 8th December. This appears to correspond to the period of high magnitude discharge values. The sine and cosine model predicts the end of May and beginning of June as periods with the lowest discharge readings, but the trend in discharge data seems to be slightly offset with lowest recorded values at the end of June and beginning of July.

These results are based upon data from one study year alone. The observations of discharge seem to adhere to the functional form of sine and cosine terms for this study year. However, it cannot be assumed that conditions within seasons will remain consistent over subsequent years and basing seasonality on date itself may prove problematic (Helsel & Hirsch, 1992). Unfortunately, the data set is not a complete annual record with a gap during spring. It is therefore impossible to test the applicability of the functional form of sine and cosine on an annual basis for this data set. However, application of this model has provided valuable information on the

Figure 6.9 Determining seasonality in suspended sediment and discharge data from the Burnhope system using sine and cosine functions.



seasonal behaviour of sediment through the Burnhope system for the majority of the year and provides the next step from simpler bivariate analysis using rating relationships.

In summary, the seasonal curves are the most appropriate for estimating Burnhope loads, while for the Langtae catchment in the absence of data for seasonal curves, the best estimate is generated through the application of the general rating curve.

6.6 Storm event analysis: suspended sediment yields and patterns of suspended sediment transfer

6.6.1 Introduction and aims

The aims of this storm event analysis section are to consider the patterns of sediment transfer during individual storm events and investigate the use of the rating curve models developed in part one to predict suspended sediment concentrations during storm events in the Burnhope catchment. Analysis of hysteresis loops for individual storm events highlight the complexity inherent in sediment transfer in upland catchments. The rating curve approach is then applied to suspended sediment concentration and discharge data from the storm events monitored in the Burnhope catchment and comparisons are made between the predicted yields estimated using the models and actual loads. Analysis of the contemporary rainfall record from the Burnhope Reservoir monitoring site provides context for assessing the significance of sediment transfer in the storm events monitored.

6.6.2 Advances in storm sediment yield prediction

Storm sediment yields have been modelled using both inductive and deductive methods. Walling and Webb (1982b) comment on the majority of models being deductive due to the general lack of detailed data on suspended sediment transport. Labadz's (1988) study of storm sediment yields in South Pennine catchments is an example of the inductive approach to developing theories of sediment transfer in headwater catchments.

Recent advances in conceptual modelling of suspended sediment dynamics have included a number of physically-based erosion models (Wicks and Bathurst, 1996;

Dietrich *et al.*, 1999) that use a series of mechanic and hydraulic equations to describe the erosion and transport of sediment in catchments (Picouet *et al.*, 2001). Other conceptual models include those based on the Instantaneous Unit Sediment Graph (IUSG) (Kazimierz, 1995) and supply-based models (VanSickle and Beschta, 1983; Asselman, 1999). These supply-based models incorporate sediment storage into the basic power function of the form $C = aQ^b$. The work of VanSickle and Beschta (1983) focuses on the supply exhaustion effect as concentrations at a certain discharge decrease over time in particular over the space of a year. The results demonstrate that knowledge of sediment supply can improve predictions of suspended sediment concentration during storm events. A simple supply-model was modified to incorporate sediment sources activated at different flow depths. The use of models that account for sediment supply is best suited to flashy systems such as Burnhope. In order to develop sediment transfer models for sediment systems in the Burnhope and Langtae catchments further analysis is required on sediment sources, their connection to the channel system and the transfer of this sediment during storm events. The next section of this chapter looks at the use of the least squares regression approach to predict suspended sediment yields for individual storm events. The predicted yields are compared to actual monitored yields to test the accuracy of the rating curves model approach for yield prediction in the Burnhope catchment. This analysis is a first step in modelling sediment supply and transfer in previously un-gauged North Pennine catchments.

6.6.3 Methodology applied to Burnhope storm data

From investigations into the relationship between sediment concentration and discharge using the rating curve approach it is clear that there are seasonal effects on basin sediment delivery (Sections 6.4 and 6.5). Several workers have isolated this seasonal effect on sediment transport (Hall, 1967; Walling, 1974; Labadz, 1988; Dietrich *et al.*, 1999) while some have analysed individual events in detail looking at patterns of sediment transfer (hysteresis) and sediment availability (exhaustion) (Walling, 1974; Bogen, 1980; Carling, 1983; Labadz, 1988; Goodwill *et al.*, 1995). In this study the seasonal effect and rating curve models based on seasonal data sub-sampled from the Burnhope data set are used to predict sediment yields from storm events while patterns of sediment transfer are investigated using event hysteresis. These findings provide a useful starting point for isolating and interpreting basin sediment delivery over shorter timescales. The number of storm events analysed is limited due to truncation of sampling caused by the Foot and Mouth outbreak.

For six storm-events monitored between 25/10/00 and 08/12/00 sediment yields in tonnes have been calculated. These actual storm sediment yields for individual events were calculated by summing the total suspended sediment loads determined from samples taken at 15-minute intervals during each event. Three rating curves were used to estimate suspended sediment concentrations from stream discharge monitored at 15-minute intervals and this formed the predicted sediment loads using the rating curve model. The rating curves used include the general, second five-monthly period, autumn (BS01 to 05) and Winter (BS06) curves. Ferguson and Smearing bias correction factors were applied to predicted yields from each curve.

6.6.4 Comparison between actual and predicted sediment yields from individual events

The actual and predicted loads and predicted loads as percentages of the actual loads are shown in Table 6.6. The actual yields calculated for the six storm-events range from 0.8 to 4.8 tonnes. The uncorrected predicted loads overestimate the actual loads when applying the general and second five-monthly period rating curves by between 6.6 and 166% with the exception of event BS05. With the introduction of correction factors, the overestimates are increased to between 49 and 279%. When the autumn rating curve was applied to events BS01 to BS05 and the winter rating curve to event BS06, predicted loads overestimated actual loads in both corrected and uncorrected cases for events BS03, 04 and 06 by between 40 and 164%. The remaining three storms using the autumn rating curve underestimated both uncorrected yields by between 29 and 62%. Correcting these predicted loads using Ferguson and Smearing correction factors increased the accuracy of these underestimates to between 12.3 and 55%.

Storm event BS05 produced a yield of 4.8 tonnes, the highest of the six events. When predicting yields from all three rating curves, both corrected and uncorrected yields underestimate actual yields by between 4.2 and 62.3%. Storm events BS03, 04 and 06 produced lowest yields and recorded the lowest peak discharges. These events record exaggerated overestimated predictions on application of all three rating curves.

The yields in Table 6.6 demonstrate the inherent uncertainties in estimating yield from rating curve regression analysis. Caution must be taken when attempting to estimate yields on a individual storm basis from a rating curve model that estimates the average

Table 6.6 Predicted sediment yields for corrected and uncorrected rating curves both as individual yields and as percentages of the actual yields.

			Using full rating curve			Using 2^{nd} period of 5 months rating curve			Using seasonal (Autumn) rating curve (Winter curve used for BS06)		
Storm event	Date	Actual yield (t)	Uncorrected	Plus Ferguson	Plus Smearing	Uncorrected	Plus Ferguson	Plus Smearing	Uncorrected	Plus Ferguson	Plus Smearing
BS01	25/10	2.83	3.39	4.78	4.95	3.54	4.90	5.06	2.00	2.38	2.48
			(19.9)	*(68.7)*	*(74.8)*	*(25.2)*	*(73.1)*	*(78.6)*	*(-29.2)*	*(-15.9)*	*(-12.3)*
BS02	02/11 to 03/11	2.63	2.80	3.94	4.08	2.93	4.04	4.17	1.66	1.98	2.06
			(6.5)	*(49.8)*	*(55.4)*	*(11.4)*	*(54.1)*	*(59.0)*	*(-36.6)*	*(-24.7)*	*(-21.5)*
BS03	07/11 to 08/11	0.83	2.09	2.94	3.04	2.20	3.05	3.15	1.31	1.55	1.62
			(151.9)	*(254.5)*	*(267.3)*	*(166.2)*	*(268.1)*	*(279.8)*	*(57.7)*	*(87.4)*	*(95.3)*
BS04	12/11	0.95	2.13	3.00	3.11	2.25	3.11	3.21	1.33	1.58	1.65
			(125.0)	*(216.6)*	*(228.0)*	*(137.6)*	*(228.5)*	*(238.9)*	*(40.4)*	*(66.9)*	*(73.8)*
BS05	28/11 to 29/11	4.80	3.09	4.35	4.51	3.22	4.46	4.60	1.81	2.15	2.24
			(-35.5)	*(-9.3)*	*(-6.0)*	*(-32.8)*	*(-7.1)*	*(-4.2)*	*(-62.3)*	*(-55.2)*	*(-53.3)*
BS06	08/12	1.15	1.32	1.85	1.92	1.40	1.94	2.00	2.24	3.02	3.04
			(14.7)	*(61.5)*	*(67.3)*	*(22.1)*	*(68.8)*	*(74.1)*	*(95.5)*	*(163.5)*	*(164.9)*
Total yields		13.18	14.82	20.85	21.61	15.55	21.50	22.18	10.36	12.66	13.08

(19.9) Estimated yields expressed as percentages of actual yields. Positive value = Overestimate. Negative value = Underestimate.

yields over seasonal or annual timescales. However, despite this issue of uncertainty when the predicted loads for all six storm events are summed to give a total yield, the uncorrected total yields calculated from the general and second five-monthly period curves over all six storm events provides a close estimate to actual yields. The corrected values overestimate total actual yields but the corrected total values using Smearing correction factor provides the best estimate of total yield, within 0.1 tonnes of the actual load. In summary, although for individual events the over or underestimation levels can be quite significant, once the total yield is calculated for the six events the discrepancies are reduced.

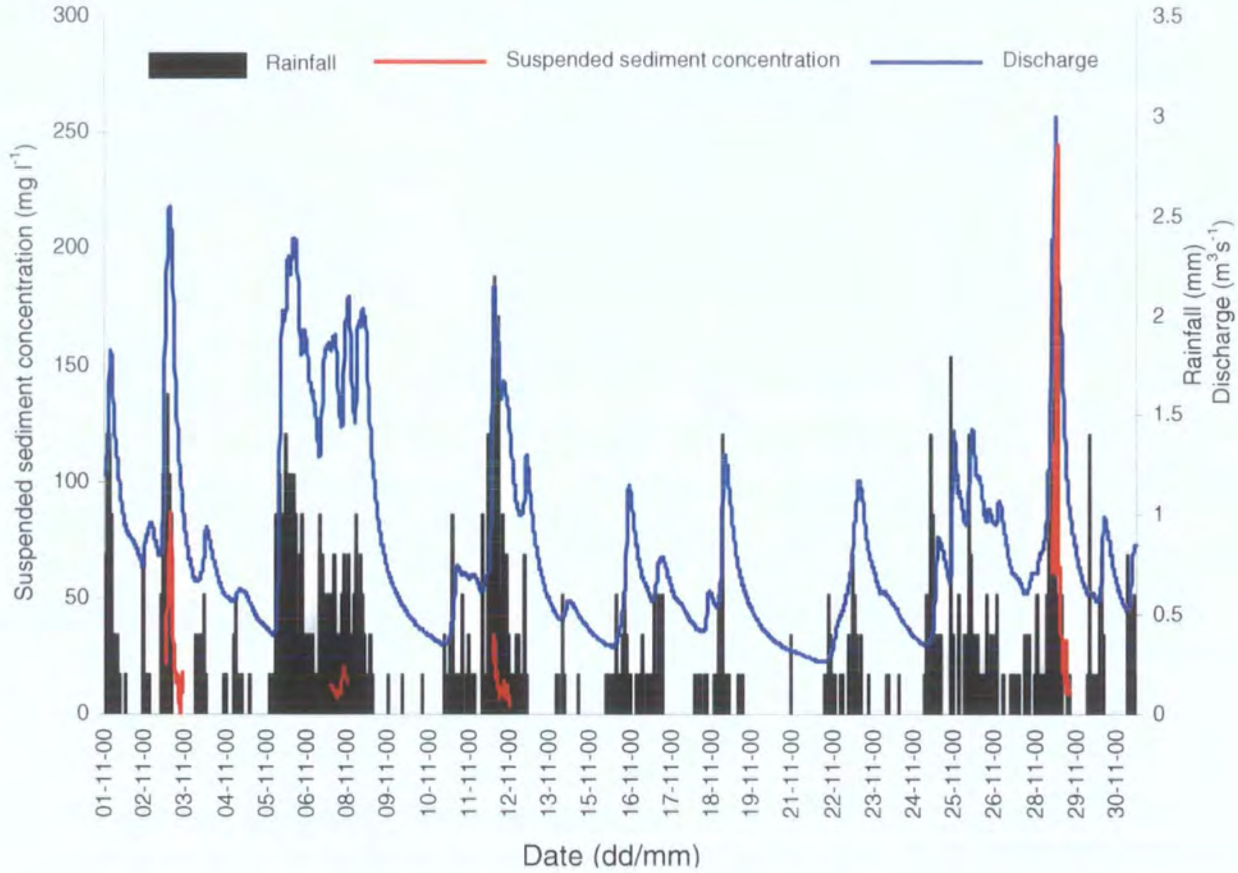
These overestimates of uncorrected yields contrast the findings of Labadz (1988) where uncorrected rating curves underestimated 55 actual storm loads in the South Pennines by more than 60%. Load estimates from the South Pennine data using the Ferguson correction factor improved the estimation to between 0.5 and 23%. These corrected factors were overestimates but were closer predictions of actual loads than their uncorrected counterparts. Although not comparable to Burnhope in terms of number of observations, the relationships between corrected and uncorrected yields within this South Pennine study are useful when investigating the application of rating curves to these small upland catchments.

Analysis of storm events in the Burnhope catchment has highlighted the flashy nature of sediment transfer in upland stream systems of the North Pennines. Although sampling was restricted to the autumn period the results have provided a detailed example of sediment transport for this period.

6.6.5 Analysis of variations in suspended sediment concentration and discharge over a month

Figure 6.10 shows a monthly time series plot of suspended sediment concentration, discharge and rainfall in November 2000. When considering the relationship between these parameters, the rapid increase in discharge with the onset of rainfall is typical of headwater stream systems due to the hydrology of these catchments being dominated by surface runoff. Peaks in suspended sediment concentration are closely related to those of discharge. Events BS03 and BS04 have significantly smaller suspended sediment concentrations than BS02 but from the graph there appears to be little variation in peak discharge timing. This may be evidence of sediment supply limitation. Within the first 15 days of November there are three main storm events that exceed discharges of 1.6 $m^3 s^{-1}$. There is a decline in SSC from approximately 70 to 35 mg l^{-1}

Figure 6.10 Comparison between suspended sediment concentration and discharge for four events sampled in November 2000.



between events BS02 and BS03/4. Event BS03 was only partially sampled so caution must be taken when using this event in comparison. There are approximately four days between BS02 and BS03 then BS03 and BS04 respectively and these short recovery periods between peak discharges could have lead to exhaustion of available sediment. For the remainder of the month, discharge reached a maximum of 1.3 $m^3 s^{-1}$ as a series of low magnitude events pass through the system. On November 28th an event with a peak discharge of 2.6 $m^3 s^{-1}$ produced suspended sediment concentrations of 249 mgl^{-1}. The peaks in suspended sediment concentration recorded during event BS05 could have been due to

1. The fifteen-day recovery period between event BS04 and BS05 that could have been sufficient time for sediment preparation processes to provide available sediment.

2. The larger peaks in discharge could have activated new sediment sources.

Further analysis of patterns of sediment transfer within individual storm events investigates the effects of sediment supply limitation in more detail.

6.7 Analysis of storm event dynamics

The term 'hysteresis' has been used by many authors to describe the relationship between sediment concentration and discharge during storm events (Bogen, 1980; Williams, 1989). Hysteresis curves can take on many different forms and Williams (1989) categorised five common classes based on establishing concentration/discharge (C/Q) ratios from graphs of sediment concentration and discharge. These include single lines or curves indicating a positive relationship between discharge and concentration, through to clockwise and anti-clockwise loops and complex figure eight curves for alternative concentration/discharge relations (Williams, 1989). Discussion of Figure 6.10 has shown the temporal concentration/discharge (C/Q) and rainfall relationships for event BS02 to BS05. The temporal C/Q relationships for each of the four events is plotted individually in Figure 6.11 and their relevant hysteresis plots are presented in Figure 6.12. The hysteresis loops are classified using the system established by Williams (1989) on C/Q criteria and this is shown in Table 6.7.

The values of C/Q ratios are important in establishing storm hysteresis (Williams, 1989). They are calculated below using the method of Williams (1989). The rising limb

Figure 6.11 Time series plots of suspended sediment concentration, discharge and rainfall for individual storm events (A) BS02 (B) BS03 (C) BS04 and (D) BS05.

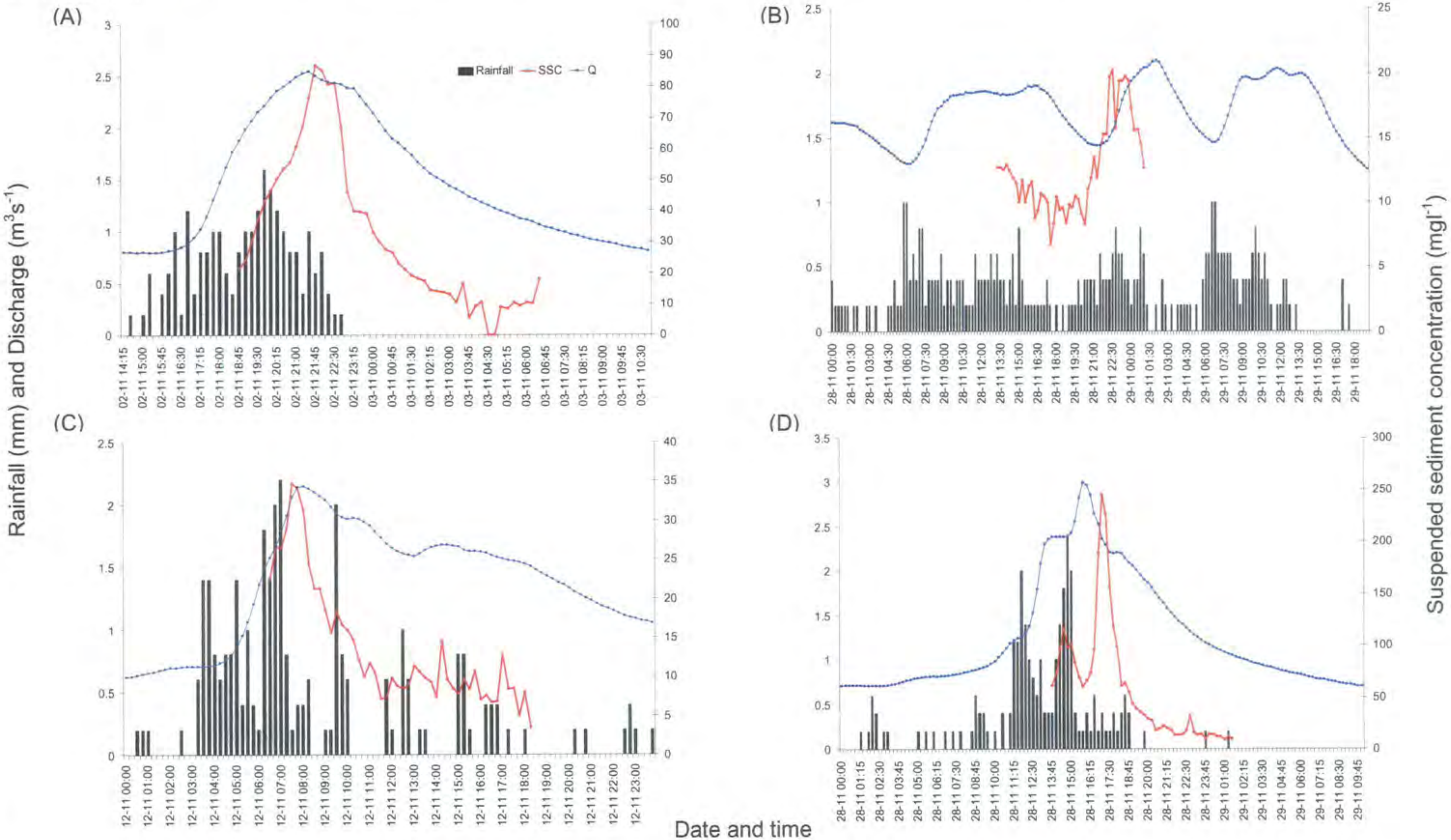
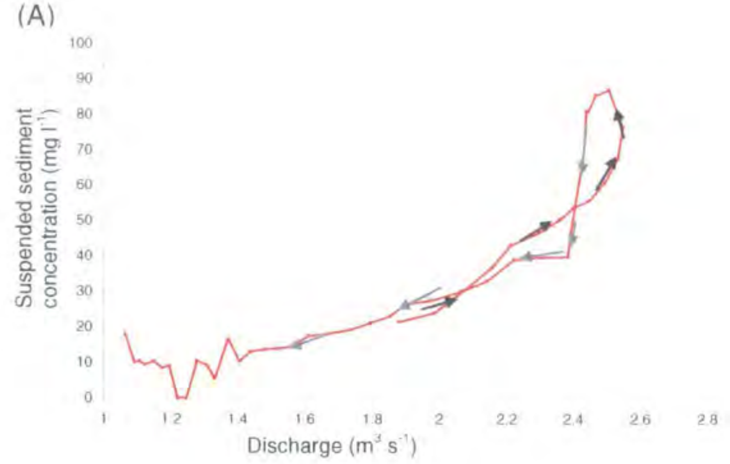
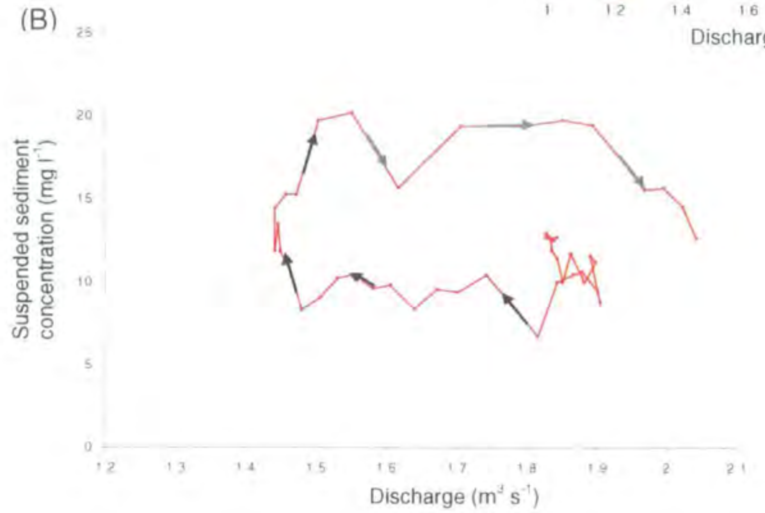
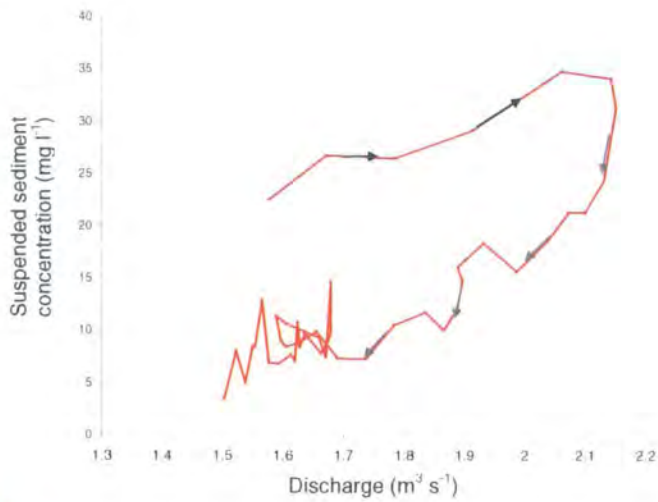


Figure 6.12 Concentration/discharge hysteresis loops for individual storm events (A) BS02, (B) BS03, (C) BS04 and (D) BS05.







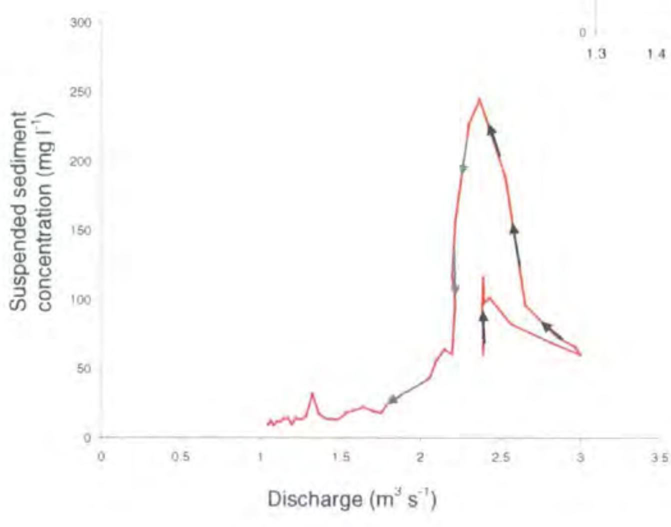


Table 6.7 The classes of concentration / discharge (C/Q) criteria and hysteresis categories of Burnhope storm events.

Class	Relation	C/Q criteria	Relative timings of discharge peak to SSC peak (hours)	Storm event	Total sediment yield (tonnes)
II	Clockwise loop	(C/Q)r > (C/Q)f for all values of Q	-4	BS03*	0.828*
			-0.75	BS04	0.948
III	Anti-clockwise loop	(C/Q)r < (C/Q)f for all values of Q	1.5	BS05	4.798
V	Figure eight	(C/Q)r < (C/Q)f for one set of values (C/Q)r > (C/Q)f for other set of values	0.25	BS02	2.625

*Multiple peaked event, only small section of storm sampled and only calculated part of total sediment yield for event.

(Modified from Williams, 1989)

ratio is established using concentration and discharge values at selected times on the rising limb of the discharge curve:

1) $C_1/Q_1 = (C/Q)_r$ (Equation 6.7)

By locating the same discharge value on the falling limb of the discharge curve and recording the concentration, the falling limb ratio is established:

2) $C_2/Q_1 = (C/Q)_f$ (Equation 6.8)

The C/Q criteria for the different hysteresis events are listed in Table 6.7. To take a more detailed look at storm sediment dynamics, the temporal concentration/discharge (C/Q), rainfall relationships and hysteresis curves are discussed for a series of four storm events (BS02, BS03, BS04 & BS05) monitored during November 2000.

6.7.1 Sediment dynamics of individual storm events

6.7.1.1 Event BS02

The slope of the rising limb of the suspended sediment concentration graph (Figure 6.11A) is greater than the rising limb of discharge. The discharge peaks 15 minutes before suspended sediment concentration whilst the peak in rainfall precedes both concentration and discharge recording a maximum of 1.6 mm. Suspended sediment concentrations range from 20 to 80 mg l^{-1} with the peak in suspended sediment occurring 15-minutes after the peak in discharge. The steep rising limb of concentration could be a result of entrainment of fine sediments from toe deposits of stream-side scars as the flow increases. After the peak in concentration is reached, there is a sharp decline in sediment concentration that drops below those recorded on the rising limb. This results in the formation of a narrow, anti-clockwise loop during the period of high discharge (Figure 6.12A). This narrow loop is indicative of short lag times between C/Q) peaks and the differing relative spread of the discharge and concentration curves (Williams, 1989). This narrow loop could indicate the supply of sediment from a source in close proximity to the gauging station that remain undiluted. The steep declining limb of the concentration graph could indicate one of the following:

1. Sediment exhaustion as the rising stage of the river had removed any prepared sediment on the channel banks, exhausting sediment supply as stage declines.

2. Peak discharge with high mean velocity activates a limited supply of fine sediments from the toe of stream-side scars that becomes quickly exhausted.

Finally, a clockwise loop is formed momentarily as the same suspended sediment concentration levels are recorded for the same discharge on the rising and falling limb of the discharge hydrograph. Overall the hysteresis loop is shaped as a figure eight (Table 6.7 & Figure 6.12A).

6.7.1.2 Event BS03

Sampling during this storm event began on the falling limb of a previous event and is therefore difficult to interpret as only a section of this multi-peaked discharge event could be monitored. Figure 6.10 highlights the small section of the multi-peaked event that was sampled. Figure 6.11B examines the relationship between suspended sediment concentration, discharge and rainfall more closely while the corresponding hysteresis loop is presented in Figure 6.12B. The hysteresis loop shows a confused signal as sampling is initiated, that could be a result of numerous internal and external sources simultaneously contributing to the sediment signal (Bogen, 1980). The variability in concentration and discharge (Figure 6.11B) and the lag time of four hours between the successive peaks produces a clockwise hysteresis curve (Figure 6.12B) with wide breadth (Williams, 1989). The steep rising limb of the concentration curve peaks at a trough in discharge, at the base of the falling limb of the proceeding discharge hydrograph. This could indicate the movement of sediment eroded by the previous event that is no longer diluted by peak discharges. Concentration levels are maintained around peak values until discharge increases inducing the falling limb of concentration. This could again be due to dilution of available sediment by increased discharge.

This concentration curve is an example of sediment exhaustion within the Burnhope system. Steady rainfall intensities between 0.5 and 1.5 mm are recorded over a 48-hour period and relate to a series of peak flows. This series of discharges and continuous rainfall will have exhausted all the active sediment sources from the system and activated new sources as channel banks become saturated and susceptible to erosion by cantilever failure.

Channel bank failure is a possible sediment source during these multi-peaked events in Pennine streams. These saturated banks are undercut by rising flood waters become top heavy leading to the collapse of cantilever blocks into the channel (Thorne and Tovey, 1981). This can occur after passage of the initial pulse of discharge.

6.7.1.3 Event BS04

Both concentration and discharge graphs are positively skewed, have similar spread and steep rising limbs resulting in concentration peaking before discharge (Figure 6.11C). This forms the wide hysteresis curve shown in Figure 6.12C as $(C/Q)_r > (C/Q)_f$ forming a class II clockwise curve inline with Williams (1989) classification (Table 6.7). The sediment yield from this event appears relatively low at 0.95 tonnes when compared to BS02 at 2.63 tonnes. Both events record similar maximum rainfall intensities of 2.3 mm and discharge readings of 2.3 $m^3 s^{-1}$. This is due to there being insufficient time for sediment preparation since the previous multiple peaked-event. The clockwise loop (Figure 6.12C) with concentration preceding discharge could be due to erosion of stored in-channel sediment resulting from the preceding event or activation of sediment deposited on the rapid falling limb of the previous event. Carling (1983) proposed the possible explanation for the concentration peak preceding discharge as the effect of rapid sediment exhaustion of the immediate in-channel sediment supplies.

6.7.1.4 Event BS05

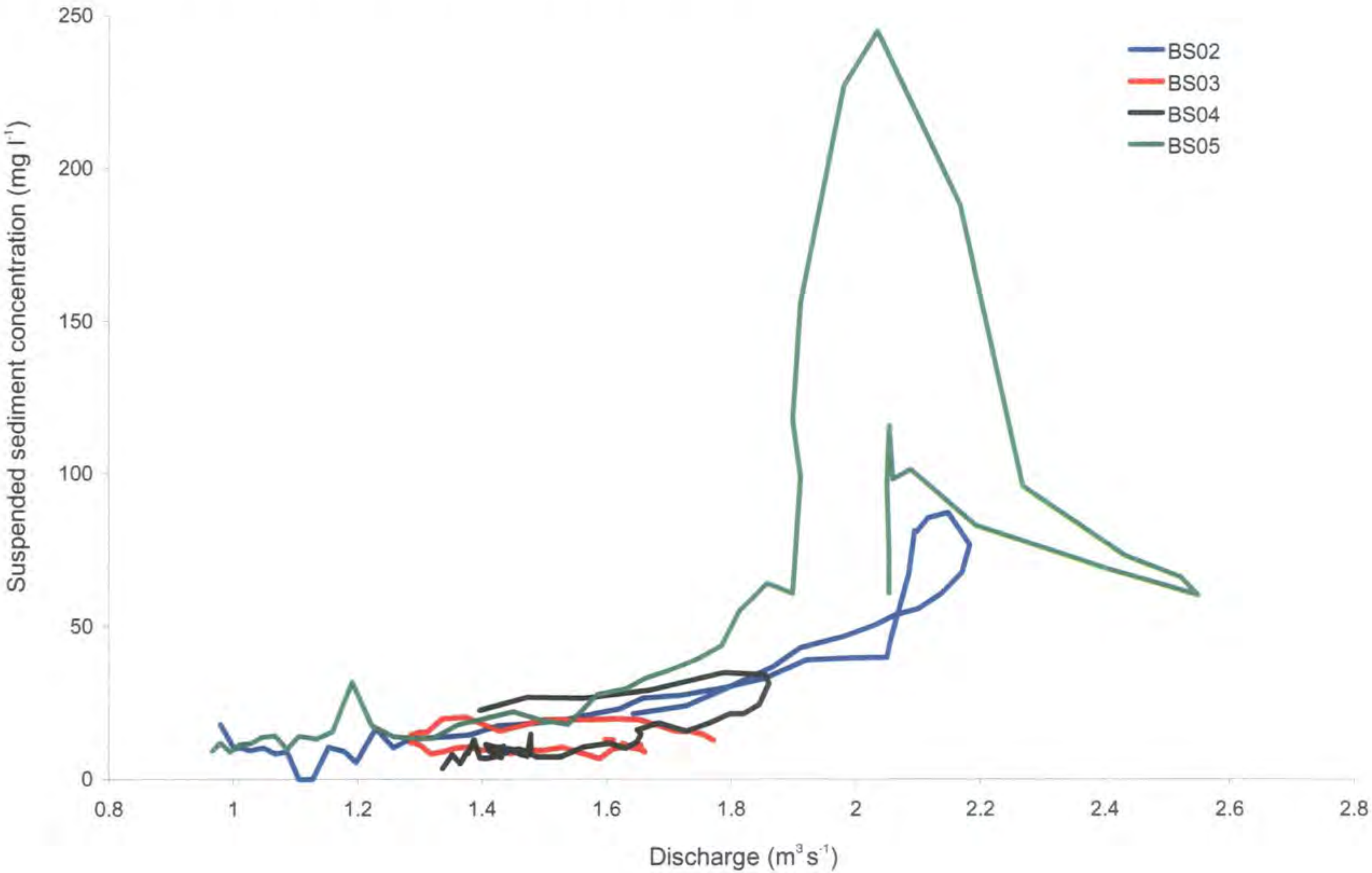
BS05 is a multi-peaked event with two peaks in rainfall intensity that results in double peaks for discharge and suspended sediment concentration. Figure 6.11D shows the first rising limb of discharge increase to 2.5 $m^3 s^{-1}$ in response to rainfall intensities of 2.1 mm per 15-minutes. The rising limb of the first suspended sediment concentration peak is initiated as discharge plateaus and rainfall intensity troughs to 0.5 mm per 15-minutes. Suspended sediment concentration peaks at 110 mg l^{-1} while discharge continues to plateau at 2.5 $m^3 s^{-1}$. The suspended sediment concentration peak could be a result of the rising limb of discharge activating sediment that travels downstream in pluses of sediments (Bogen, 1980).

Once the second peak in rainfall is reached at 2.4 mm per 15-minutes, discharge increases once more to 3 $m^3 s^{-1}$. This peak corresponds to the base of the rising limb of suspended sediment concentration, which then rapidly increases to 250 mg l^{-1} on the falling limb of the discharge hydrograph. The sediment exhaustion effects shown by the decrease in suspended sediment concentration at constant discharge during the first episode of this multi-peaked event, indicates that the sediment transported during the second episode is either from a different sediment source or was activated during the second episode rainfall and discharge peaks. The second episode of rainfall could have activated channel bank sources that were then transported during successive peak discharges. Whatever the provenance of the second episode suspended sediment concentration peak it was easily exhausted as represented by the steep rising and falling limbs. The hysteresis plot falls into class III of Williams (1989) classification (Table 6.7) producing an anti-clockwise loop where $(C/Q)_r < (C/Q)_f$ for all values of discharge. It provides the only example of anti-clockwise hysteresis for this set of storm samples. The suspended sediment concentration peak for the first episode is clearly defined with increasing suspended sediment concentration from 60 mg l^{-1} to 120 mg l^{-1} at a discharge of 2.3 $m^3 s^{-1}$. The exhaustion effect is evident with a decrease in suspended sediment concentration as discharge increases. The narrow envelope of the loop is indicative of the flashy sediment transport regime of this system.

6.7.2 Discussion of events BS02 to BS05

When comparing the hysteresis curves of BS02 to BS05 it is evident that each event has a different pattern of sediment concentration and discharge and a complex relationship exists between catchment processes and resulting sediment transport. Figure 6.13 shows a summary plot of all storm event hysteresis curves. There is an overall increase in sediment concentration with discharge, but on an individual storm basis the transport of sediment is not dependent upon discharge alone. During all four events, the limbs of the suspended sediment graphs are much steeper than those of discharge. This indicates that while suspended sediment transport is triggered by discharge, discharge levels alone are not capable of maintaining concentration levels. This point was also made by Carling (1983) when he concluded that sediment-laden flows are rarely near hydraulic capacity. Carling (1983) also commented that sediment supply might frequently be more important than the hydraulic controls in regulating the output of sediment from a basin. At Burnhope, sediment supply appears to play an influential role in determining suspended sediment yields.

Figure 6.13 Comparison between hysteresis curves for Burnhope storm events BS02 to BS05.



6.8 Analysis of the contemporary rainfall record

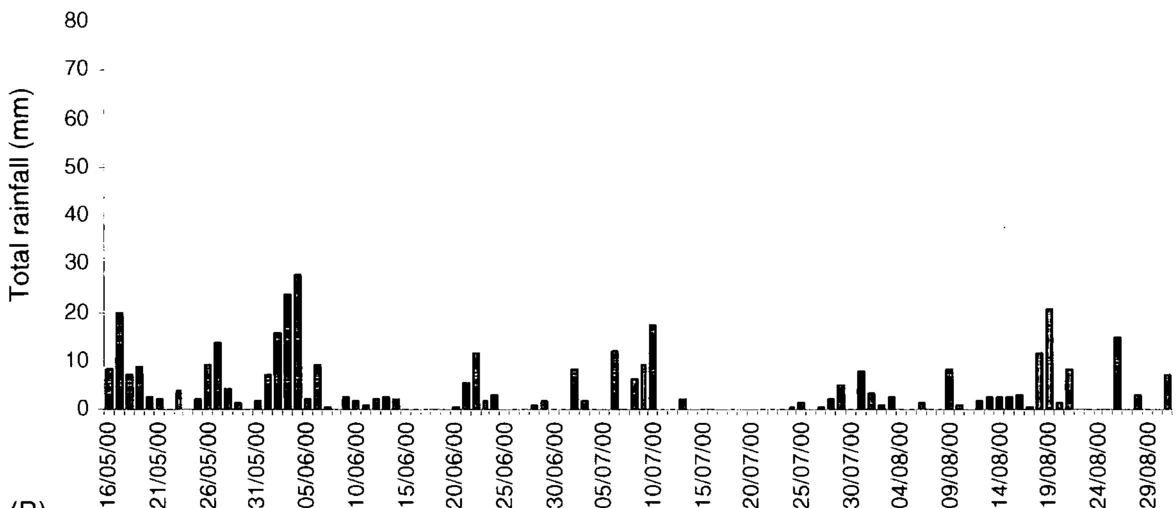
The magnitude and frequency of rainfall recorded in the Burnhope catchment from May 2000 to February 2001 at 15-minute intervals can be investigated to provide context for the events monitored in November 2000. Figure 6.14 shows the daily rainfall intensities for the Burnhope catchment over the summer (a), autumn (b) and winter (c) of the 2000-01 monitoring period. The episodes of precipitation occurring during the summer appear rather flashy in nature with intermittent dry spells. During the autumn months the frequency of rainfall and maximum intensities increase. The frequency of precipitation increases at the end of October to the middle of November during which time storm sampling of suspended sediment at 15-minute intervals was initiated. In the winter period, there are the smallest number of episodes recording rainfall. These occur at the end of December and from the middle to end of January. There are numerous episodes recording no rainfall. These could be periods of snowfall that are likely considering the average upland temperatures recorded during these winter months (1992-1999) are –0.6 and 0.3°C respectively (Table 3.7).

Hourly rainfall intensities for the same seasonal periods are shown in Figure 6.15. These plots provide a more detailed account of the nature of the rainfall events within the Burnhope catchment by providing the morphology of the storm hydrographs. Comparison between the daily and hourly plots highlights the important detail of magnitude and frequency of rainfall intensity that is missed on the daily plots. An example is the event occurring between 06/11/00 and 08/11/00. There is a pattern of continuous rainfall recorded on the hourly rainfall plot for autumn that is only recorded as two days of heavy rain on the daily plots. Rapid variations in the intensity and duration of rainfall events in upland catchments appear to be masked by analysis of daily totals alone.

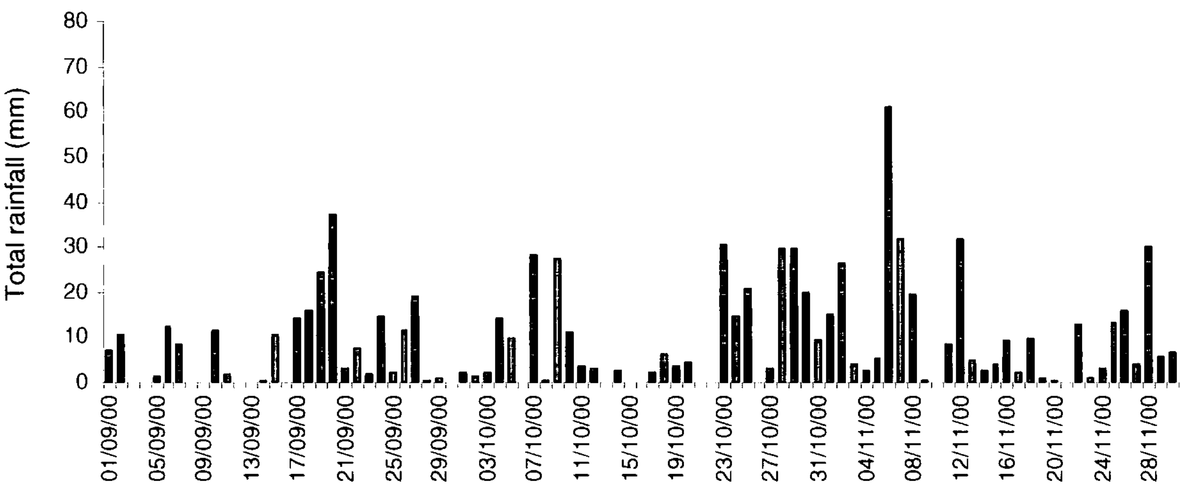
The mean rainfall intensity of 0.23 mm hr^{-1} was recorded for the contemporary study period, which is comparable to the intensity estimates of 0.32 mm hr^{-1} calculated from mean monthly rainfall records from Grassholme Reservoir in Teesdale for the year 1979 to 1980 (Carling, 1983). Carling (1983) attributes the seasonal discrepancies in duration and intensity of precipitation to the occurrence of snowfall and to the inability of obtaining accurate estimates of this type of precipitation. Unfortunately, there is only a very patchy dataset representing the spring months of March, April and May, so estimates of annual mean rainfall intensity are not available. In an attempt to examine the magnitude, frequency, intensity and duration of these rainfall episodes within the

Figure 6.14 Daily rainfall totals for (A) Summer (B) Autumn period and (C) Winter period.

(A)



(B)



(C)

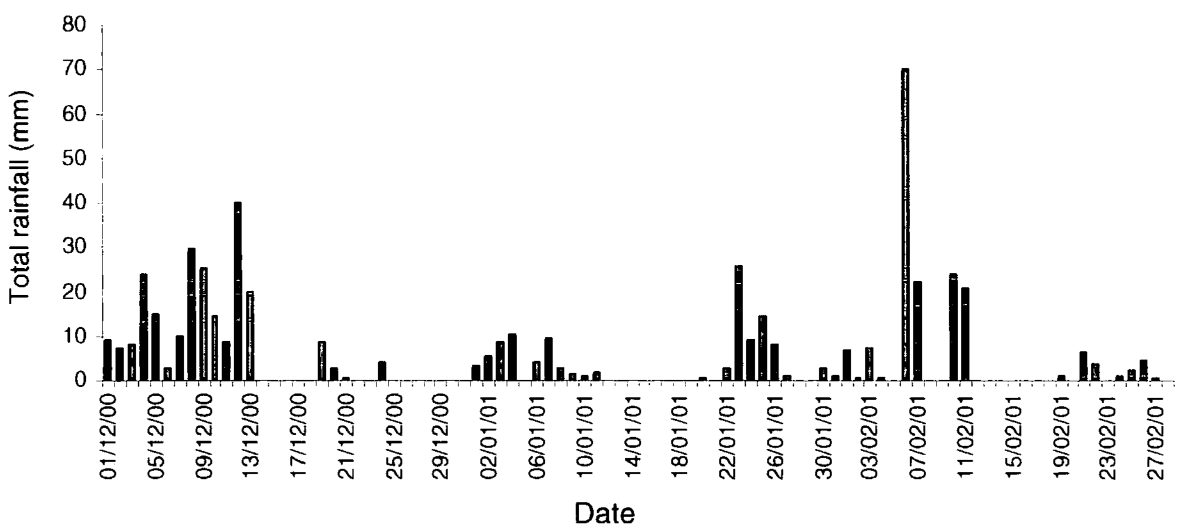
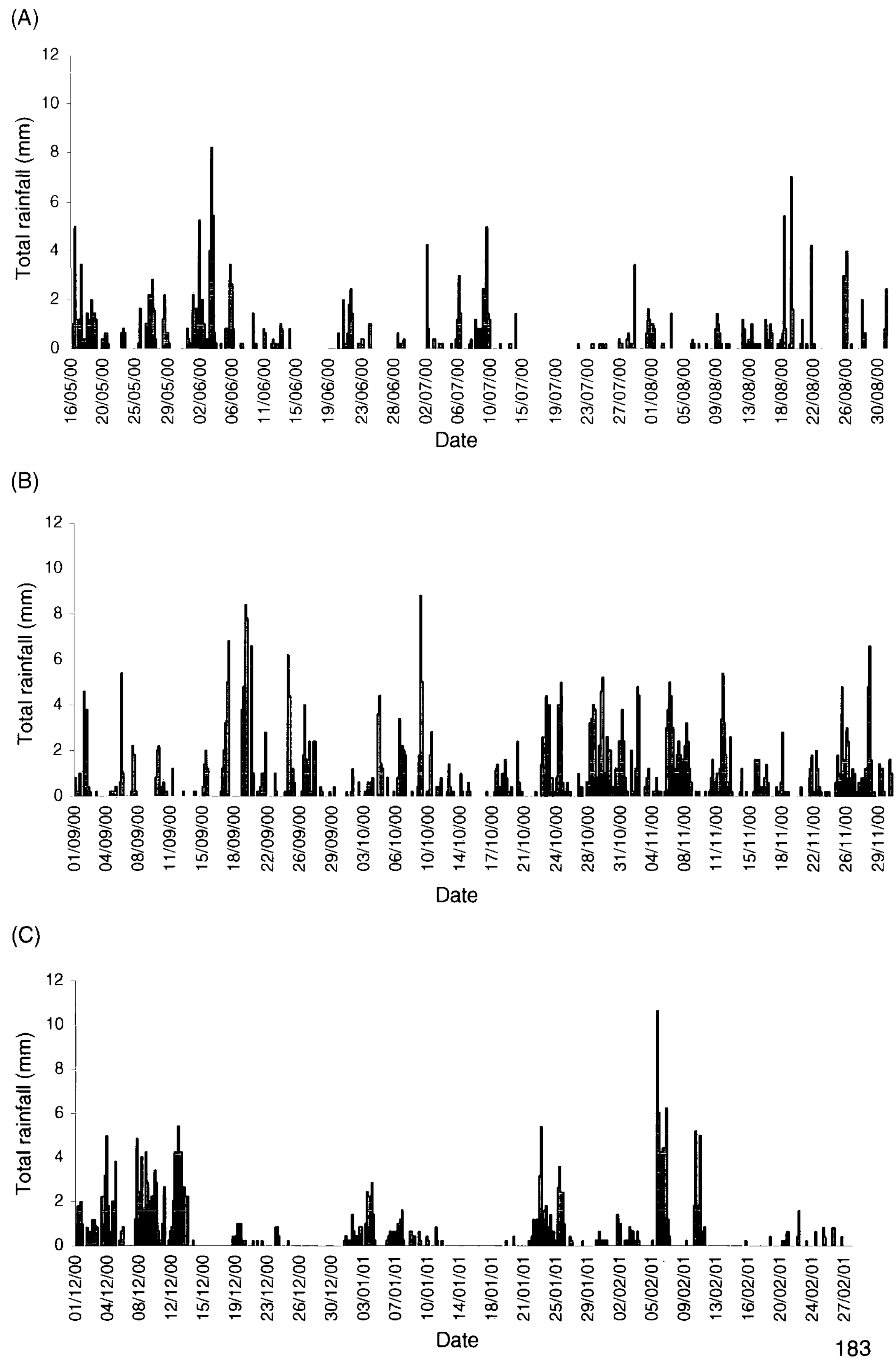


Figure 6.15 Hourly rainfall totals for the (A) Summer (B) Autumn and (C) Winter period.



contemporary dataset, the record was filtered to determine the number and timing of rainfall events between May 2000 and February 2001.

6.8.1 Determination of a storm event: results of intensity and duration analysis

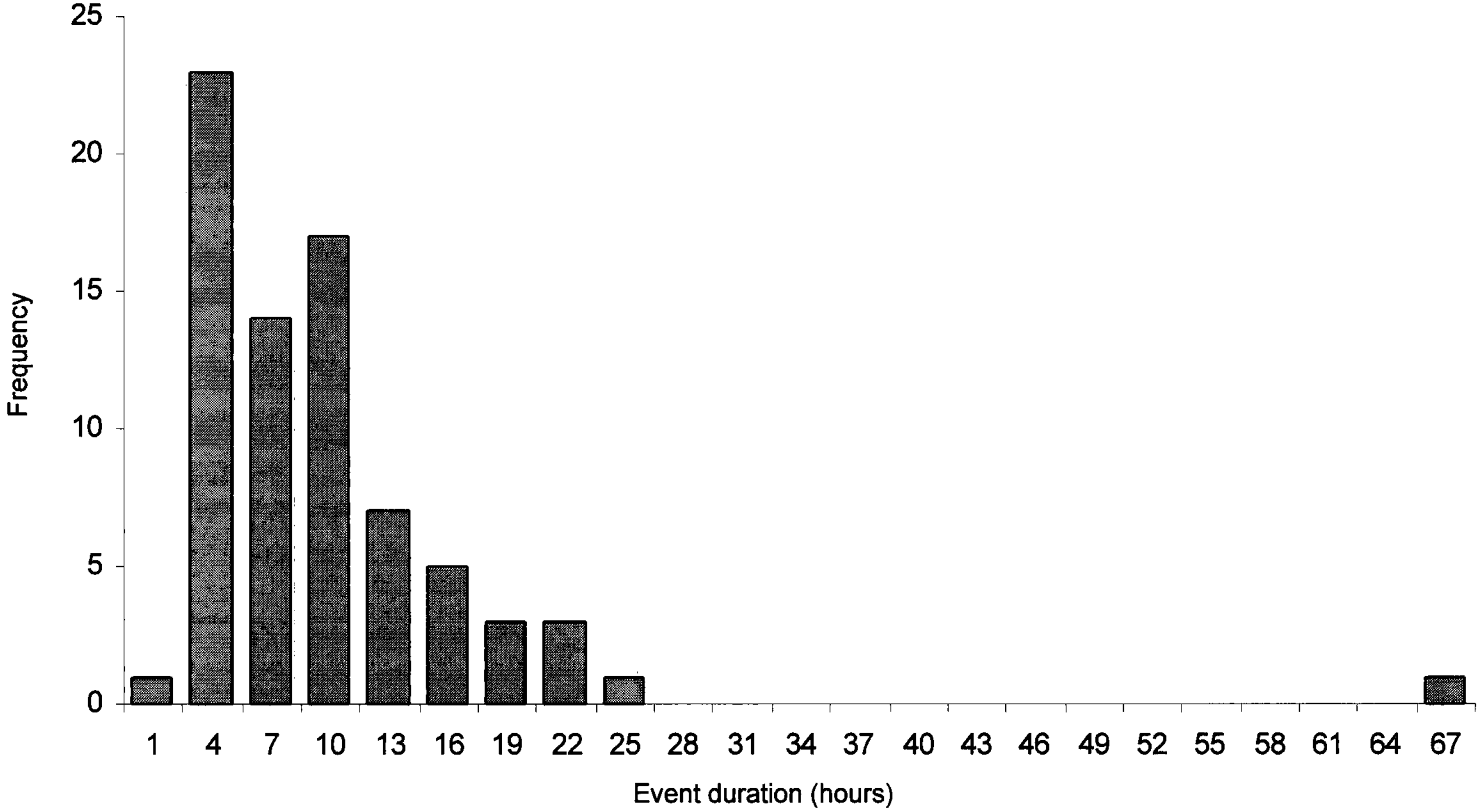
The mean intensity of rainfall recorded on a 15-minute basis from May 2000 to February 2001 (the contemporary monitoring period) was 0.5 mm. Based on this mean intensity, for the occurrence of rainfall to be classified as an event, the hourly intensity must exceed 2 mm hr^{-1}. Any rainfall recorded before or after this threshold intensity was included in the calculation of total event rainfall and mean intensity. The beginning and end of an event was specified where zero rainfall was recorded for a minimum of one hour. Any rainfall episode that did not record 2 mm hr^{-1} intensity at any point in its duration was not specified as a storm event. Using this rationale, 75 events were determined from the contemporary rainfall series. These events were analysed on a seasonal basis and summarised in Table 6.8. During the autumn months 47% of the events occurred. This period also recorded the highest average and maximum duration of events. The average duration of winter events is similar to those of the autumn period but the average duration of the summer events is only 56% of that recorded during the autumn. The total rainfall recorded throughout this study period is 1736 mm. Of this total, 37% fell during storm events in the Autumn period, 22% during the winter and 12 % during the summer period. In total, 71% of the total rainfall recorded during the study period fell within the 75 storm events leaving 29% of the total from rainfall episodes recording an intensity of < 2 mm hr^{-1}.

Over two thirds of the total rainfall fell during these storm events; therefore further analysis into the frequency distribution of event duration and maximum rainfall intensity provides important information on the most appropriate timescales for rainfall analysis in upland catchments. Figure 6.16 shows the frequency distribution of event duration with 98% of events lasting less than 25 hours. Many rainfall records, especially historic measurements, taken on a daily basis. The results from Figure 6.16 clearly highlight the problems with using daily totals for the Burnhope catchment. One daily total could contain a number of storm events, masking the occurrence of events of different intensities. Another problem with daily totals is the timing at which the measurement is made. Many events may be split and recorded as separate events over two or more days. In order to test this hypothesis, the start and finish dates and times of the 75 storm events were filtered to calculate what percentage of events would be split if sampling at Burnhope during the contemporary study period was on a daily basis. Two sampling times of 9 am and 5 pm were selected to test the hypothesis as

Table 6.8 Summary of seasonal storm event statistics for the monitoring period May 2000 to February 2001

	Summer	Autumn	Winter
Percentage of events reaching intensity of >2mm hr^{-1} (%)	25	47	28
Maximum duration (hours)	17	65	24
Average duration (hours)	5.7	10.2	9.7
Maximum recorded intensity (mm hr^{-1})	8.2	8.8	10.6
Maximum mean intensity (mm hr^{-1})	3.6	4.6	4.5
Maximum rainfall total of individual event (mm)	46.8	116.4	49.2
Sum of rainfall during events reaching >2mm hr^{-1} (mm)	205.8	639	373.6
Percentage event rainfall of the total rainfall recorded throughout the monitoring period (%)	12	37	22

Figure 6.16 Frequency duration of contemporary events.



these are likely times that commercial gauge reading would take place. The results suggest that daily totals for these flashy upland catchments would not provide accurate information on event duration as between 20 and 27% of events would have been split over two days using monitoring times of 9 am and 5 pm respectively. The majority of rainfall records, especially historical ones are daily totals and care must be taken to account for these margins of error when analysing daily totals. At the opposite end of the scale, 98% of events record duration of greater than 1 hour, therefore analysis on an hourly basis appears to be the optimal increment for determining storm events in upland rainfall records.

6.8.2 Rainfall events and suspended sediment monitoring

The top 20 events recording the highest total rainfall (mm) are shown in Table 6.9. Of these 20 events, the suspended sediment concentration and discharge was measured for six of these. The maximum intensity for the six monitored events range between 4.8 and 6.6 mm hr^{-1}. The frequency of maximum recorded rainfall intensity reveals that 37% of events record between > 4.5 and 7 mm hr^{-1} intensity and therefore the suspended sediment concentration and discharge monitored events provide detailed information on the pattern and quantity of sediment transfer for over one third of above average intensity events. Only 5% of events recorded intensities over 7 mm hr^{-1} and unfortunately no suspended sediment concentration data is available for these events.

6.8.3 Return period of events

The recurrence interval for storm events can be calculated based on the daily maximum series. The largest total discharges and maximum daily rainfall intensities can be used in Equation 6.9 to assess the likely return period of events with certain maximum hourly rainfall intensities and totals. This equation was originally developed to calculate return periods from the annual maximum series based on 24-hour rainfall totals (Knighton, 1998). Use of this equation to estimate return periods on an annual basis for the Burnhope system is flawed in that the majority of 24-hour rainfall totals probably fell on a much shorter timescale as demonstrated by frequency of duration analysis (Figure 6.16). The use of 24-hour totals or intensities could greatly underestimate the return period of the rainfall. For this reason, hourly intensities have been used to estimate the return period in days of those intensities.

Table 6.9 Top 20 events based on total hourly rainfall determined from the contemporary rainfall record (May 2000 to February 2001).

Rank	Event start		Event finish		Event duration (hours)	Max intensity rainfall (mm/hr)	Total rain (mm)	SSC Sampling event	SSC sampling start		SSC sampling finish		Total SSC (tonnes in 12 hours)
	date	time	date	time					date	time	date	time	
20	26/05/00	16:00	27/05/00	09:00	17	2.8	20.2						
19	19/08/00	06:00	19/08/00	11:00	5	7.0	20.2						
18	12/12/00	16:00	13/12/00	00:00	8	5.4	21.8						
17	23/10/00	10:00	23/10/00	23:00	12	4.4	23.6						
16	02/11/00	14:00	02/11/00	23:00	9	4.8	23.8	BS02	02/11/00	18:40	03/11/00	06:25	2.6
15	17/09/00	18:00	18/09/00	06:00	12	6.8	25.2						
14	29/10/00	10:00	30/10/00	00:00	14	5.2	26.0						
13	09/10/00	11:00	09/10/00	19:00	8	8.8	27.2						
12	11/11/00	23:00	12/11/00	14:00	15	5.4	27.2	BS04	12/11/00	06:30	12/11/00	18:15	1.0
11	07/10/00	02:00	07/10/00	22:00	20	3.4	28.2						
10	28/11/00	05:00	28/11/00	20:00	15	6.6	28.2	BS05	28/11/00	13:45	29/11/00	01:30	4.8
9	23/01/01	13:00	24/01/01	08:00	19	5.4	30.0						
8	24/10/00	17:00	25/10/00	10:00	17	5.0	32.0	BS01	25/10/00	00:30	25/10/00	12:15	2.8
7	07/12/00	20:00	08/12/00	20:00	24	4.8	38.8	BS06	08/12/00	01:15	08/12/00	13:00	1.2
6	10/02/01	10:00	11/02/01	08:00	22	5.2	41.0						
5	06/02/01	16:00	07/02/01	14:00	22	6.2	42.6						
4	03/06/00	17:00	04/06/01	06:00	13	8.2	46.8						
3	06/02/00	03:00	06/02/01	14:00	11	10.6	49.2						
2	19/09/00	17:00	20/09/00	05:00	12	8.4	53.2						
1	05/11/11	21:00	08/11/00	14:00	65	5.0	116.4	BS03	07/11/00	13:15	08/11/00	01:00	0.8

$$T = \frac{(n+1)}{N}$$ (Equation 6.9)

T = return period (days)
n = number of days of record
N = rank of particular event (From Knighton,1998)

Rainfall events recording a maximum of 4.8 mm hr^{-1} have a return period of approximately 13 days, while a maximum of 6.6 mm hr^{-1} has a return period of approximately six weeks (41 days). The events that were monitored for suspended sediment concentration and discharge at 15-minute intervals recorded maximum intensities between 4.8 and 6.6 mm hr^{-1} so detailed analysis on sediment loads and discharge is available on storm events with return periods of between 13 and 41 days. The variation in sediment supply, transfer and deposition within and between events must be considered when assessing sediment transfer based on rainfall intensity and duration. Analysis of the contemporary rainfall record has placed the monitored events in context in terms of rainfall intensity and duration. However, further analysis of the storm events over longer timescales is required before this method can be used to determine sediment transfer on the basis of rainfall parameters.

6.9 Chapter summary

In this chapter sediment yields have been quantified and sediment transport regimes evaluated for the Burnhope and Langtae headwater catchments in the North Pennines for the periods May 2000 to February 2001 and July to December 2000 respectively. This study has investigated sediment delivery at the catchment scale by using data collected from the outlets of the Burnhope and Langtae drainage basins. The chapter consisted of two parts that shared the common aim of estimating stream suspended sediment yields and investigating the relationship between suspended sediment concentration and discharge for Burnhope and Langtae catchments. The first involved longer term monitoring of suspended sediment concentration at six hourly intervals and discharge at 15-minute intervals. The relationship between suspended sediment concentration and discharge has been investigated using the full and sub-sampled data sets from both catchments and the form of the regression models analysed for accuracy and precision. Variability was apparent between seasonal concentration and discharge relationships and each season appeared to exhibit characteristic sediment dynamics in response to changes in precipitation and discharge. The role of seasonality has been investigated using Fourier analysis and the trends confirm a seasonal signal in suspended sediment from discharge measurements. As a result of these findings, sediment-rating curves based on seasonal rating models are likely to provide the most precise prediction of sediment yield for the Burnhope catchment. However, due to gaps in the Langtae record, the full data set was considered the most precise model for estimating Langtae sediment yields.

Comparisons between the general rating curves for Langtae and Burnhope have been interpreted as showing differences in sediment transport regimes between catchments. Sediment transfer occurs over a shorter discharge range in the larger Burnhope system, which is related to different levels of connectivity between sediment sources and the channel. Sediment transfer occurs at lower discharges in the Langtae system reflecting increased availability of sediment supply at low flow in the smaller catchment. The lack of sediment transfer at low discharges in the Burnhope system reflects the low connectivity between sources and the channel at low discharges and supports the theory of sediment exhaustion on the falling limb of discharge hydrographs identified during intra and inter-storm event analysis.

The second part of this chapter concentrated on the detailed records of six storm events recorded from October to December 2000. Storm event yields have been predicted using the full and seasonal rating curves and compared to actual yield estimates. Uncorrected models provided the closest predictions to actual loads for events BS02, 03, 04 and 06 which contradicts the findings of Labadz (1988) for storm event analysis in the South Pennines. There are large variations in precision between estimates for each event but these variations were later related to sediment exhaustion effects when suspended sediment concentrations, discharge and rainfall time series for November 2000 were analysed. Event BS05 produced the largest sediment yield and corrected rating model predictions provided estimates within 10% of actual loads for the full rating and second five-monthly period rating curves. Analysis of the time series variations in suspended sediment concentration, discharge and rainfall suggested that the time span between events was sufficient for an abundant sediment supply to be available at the onset of BS05. This finding may support the argument that sediment supply limitation is a contributing factor to the application of bivariate rating models to predict storm suspended sediment yields in the Burnhope catchment. Analysis of the relationship between suspended sediment concentration and discharge on individual event timescales has highlighted the complexity of storm sediment dynamics, sampling of further events is required for more detailed inter- and intra-seasonal understanding of sediment transfer. These findings demonstrate the limitations of attempting to apply a univariate model to a multivariate problem (Walling and Collins, 2000) and provide an insight into the errors associated with quantifying sediment loads in North Pennine streams. It is clear that there is scope for further investigation into developing models that incorporate sampling frequency, sediment supply and hydrological variables at both the large basin and individual reach scale.

Analysis of the contemporary rainfall record revealed that over two thirds of the total rainfall fell during 75 storm events and 98% of events had a duration of greater than 1 hour. Monitored events provide detailed information on the pattern and quantity of sediment transfer for over one third of events with above average rainfall totals, a significant starting point for assessing sediment transfer in previously un-gauged North Pennine catchments.

Estimation of suspended sediment yields for the Burnhope and Langtae catchments provide an estimate of suspended sediment flux to Burnhope Reservoir, the sink for suspended sediment from both catchment systems. These fluxes will be compared to estimates of reservoir sedimentation from cores and used to calibrate longer-term sedimentation variations.

CHAPTER 7 - RESERVOIR SEDIMENTATION

7.1 Introduction

Reservoirs are localised base levels for stream systems that provide excellent sinks for catchment sediments. As flow enters the reservoir, a decrease in velocity occurs as cross-sectional area of the channel increases resulting in sediment deposition. The pattern of sediment distribution is dependent on factors including the size and texture of sediments, the physical characteristics of the reservoir and reservoir operation (DETR, 2001). Coarse-grained sediment deposition occurs in the proximal limb of the basin while finer sediments are carried further into the reservoir and settle in the distal basin. Reservoir sediment accumulation provides an ideal opportunity to investigate temporal variations in sedimentation; assess total sedimentation rates and yields; and to reconstruct historic variations in land use and climate.

A wealth of research has been carried out estimating sediment yields from individual reservoir studies as described in Chapter 2, but until recently no research had sought to combine these individual studies to assess yield estimates from British reservoirs. The aim of the most recent report prepared for the Department of the Environment, Transport and the Regions (DETR) on Sedimentation in Storage Reservoirs in Britain (2001) by Halcrow was to provide the first review of reservoir sedimentation in Britain. This report provides guidance on the prediction of storage loss and the measures that can be taken to mitigate the associated problems. A classification of reservoirs based upon catchment and reservoir characteristics from 107 sites in the UK provides a useful basis for categorising reservoir sediment yields from upland and lowland regions. This report marks the beginning of the first estimates of loss of capacity to be expected in British reservoirs based on reservoir classification and highlights the scarcity of reservoir sedimentation data available. Further work is needed on individual catchments to contribute to this database of sediment yields. Estimates of sediment yield from Burnhope Reservoir will contribute to this database of British reservoirs and form a valuable component of the reservoir sediment budget. Discussion of sediment yields from Burnhope Reservoir in relation to the classification system proposed in the DETR report (2001) is included in Chapter 8, Section 8.4.

The aim of this chapter is to estimate sediment yields from reservoir sedimentation and consider climatic variability and reservoir operations as the dominant influences affecting sedimentation in Burnhope Reservoir. The results of physical and radiometric analysis of reservoir core sediments are presented providing preliminary information on the spatial and temporal distribution of sediment in Burnhope Reservoir. Analysis of historical daily rainfall records reveals variations in the hydroclimate of the recent past, which could potentially influence sediment transfer in this upland catchment. Variations in the down core particle size records, fluctuations in reservoir levels and differences in seasonal rainfall totals over time are evaluated to assess the degree to which variations in sedimentation are related to hydroclimatic variability. Long-term sediment yields are estimated using two different approaches that are based on sediment inputs from Burnhope and Langtae Burn being the main inputs to Burnhope Reservoir. The first incorporates the use of historic rainfall records and contemporary rating curve data to determine estimates of long-term sediment yield. The second method is more conventional, incorporating core depths, radiometric dating, bathymetry and air photographs to determine the active area of sedimentation and subsequently estimate annual sediment yields.

7.1.1 Sediment cores

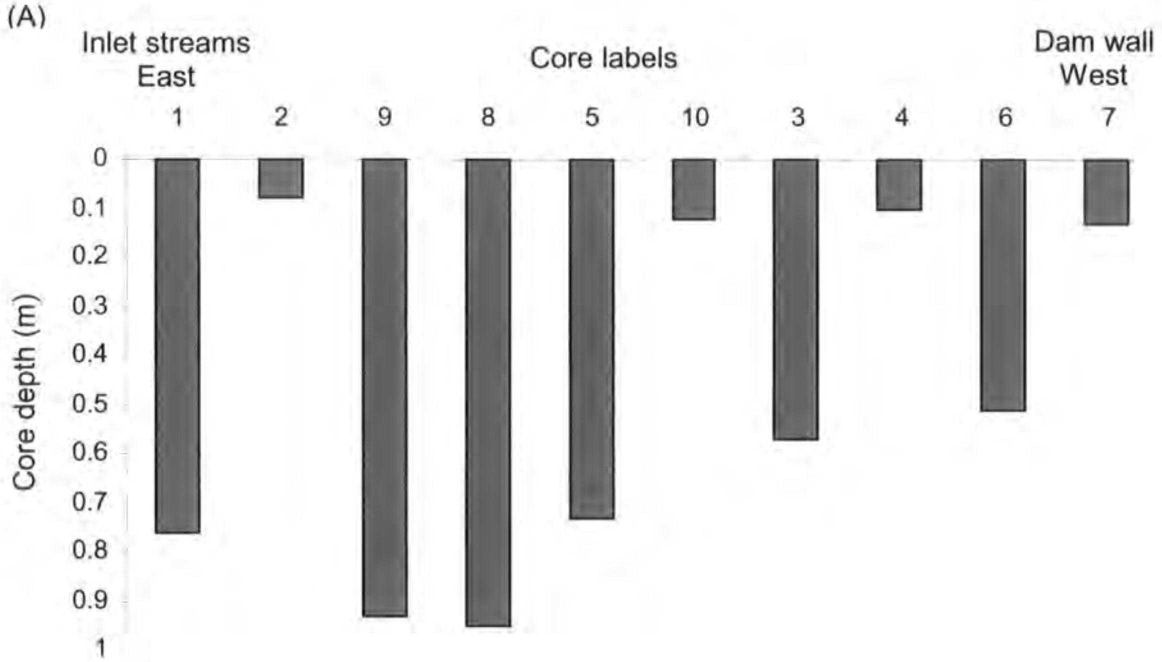
Sediment cores were retrieved from ten locations in Burnhope Reservoir as described in Section 4.4.2. The location and depth of sediment cores obtained are shown in Figure 7.1. Six of the ten cores were of sufficient depth to analyse down core variations in physical sedimentological characteristics, cores 1, 3, 5, 6, 8 and 9. Dry bulk density, percentage loss on ignition (LOI), inherent moisture content and minerogenic content of the sediments were measured at 1 cm intervals on each of the six cores as described in Chapter 4, Section 4.6. High and low frequency magnetic susceptibility was measured on three cores (1, 5 and 8) as a medium for core correlation but the measurements were found to correspond to particle size variations alone. Radiometric dating of sediments from three cores (1, 6 and 8) was undertaken using ^{137}Cs and the down core variations in these sedimentological parameters are shown in Figure 7.2 to 7.7.

7.2 Bulk sedimentological character of the Burnhope sediment cores

From observation of the general down core trends in all physical parameters in cores 1, 9, 8, 5, 3 and 6 (Figure 7.2 to 7.7 respectively) there are distinct sedimentological variations between cores. Sediment yield estimates from reservoirs tend to include both coarse and fine-grained sediments and in the case of Burnhope this includes

Figure 7.1 (A) Depths of cores taken from Burnhope reservoir plotted in relation to location on an east-west transect and (B) diagram of core locations and reservoir bathymetry.

(A)



(B)

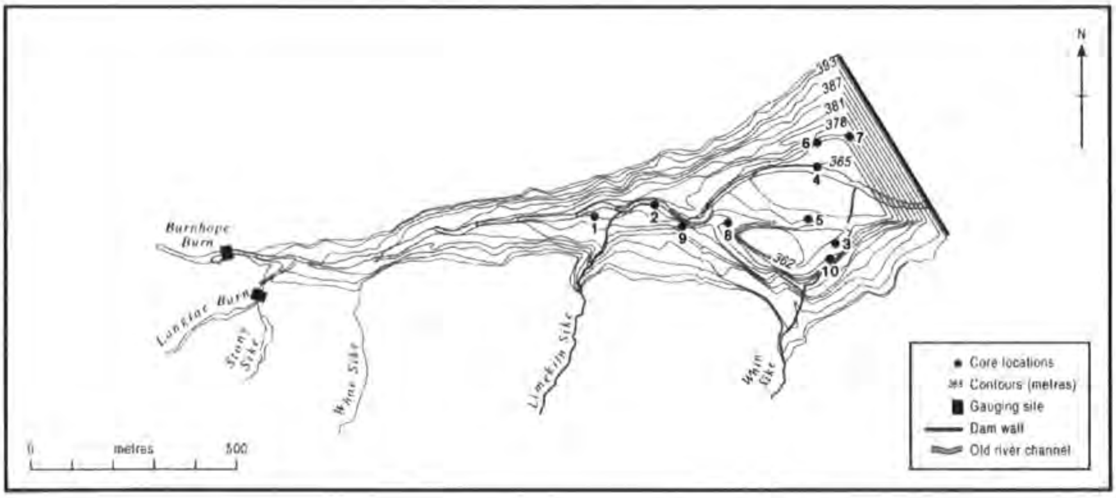


Figure 7.2 Down-core variations in dry bulk density, LOI, inherent moisture, magnetic susceptibility and minerogenic content of sediments in core 1 dated using ^{137}Cs and calibrated with ^{137}Cs fallout records for the Northern Hemisphere.

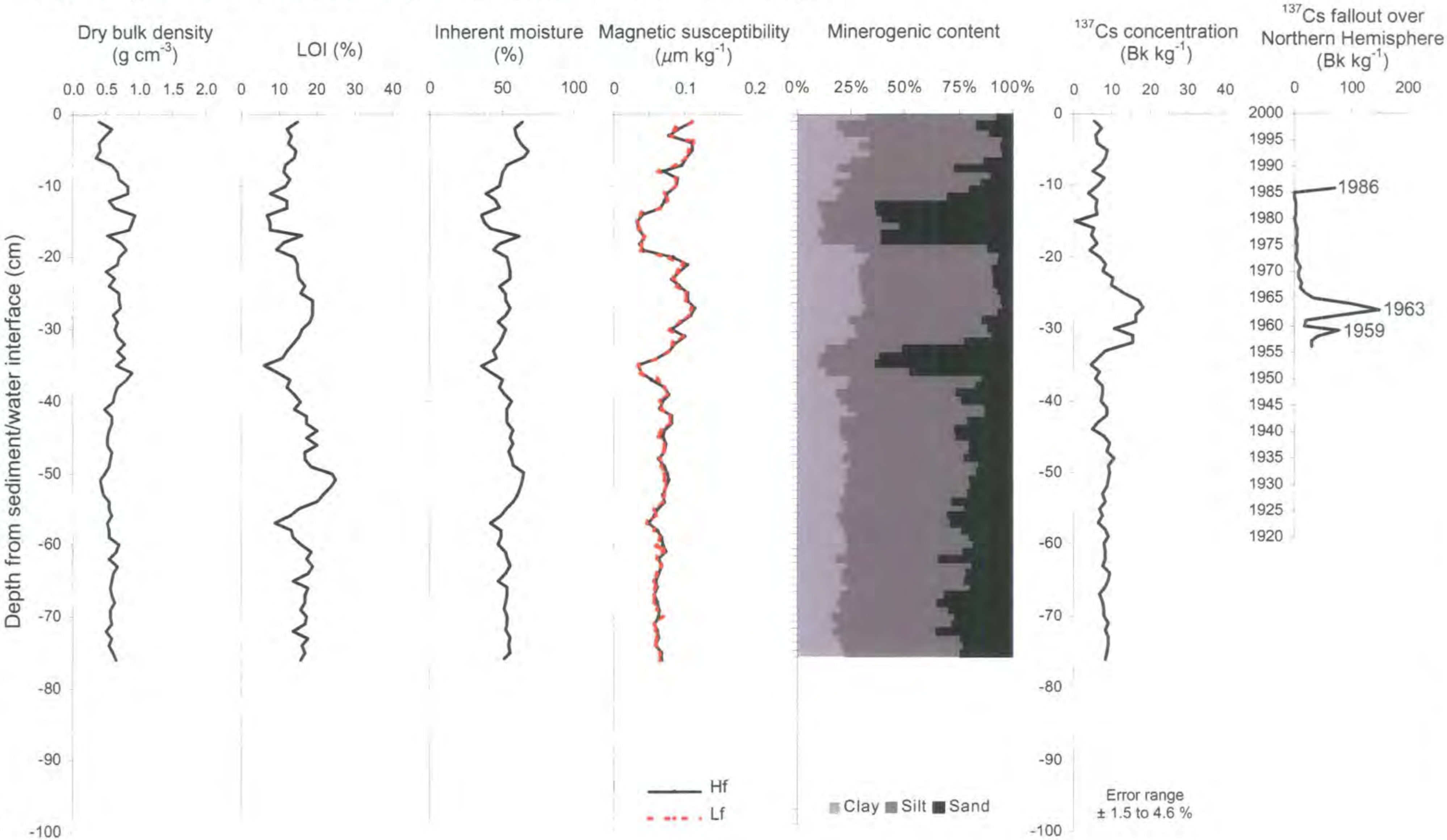


Figure 7.3 Down-core variations in dry bulk density, LOI, inherent moisture and minerogenic content of sediments in core 9.

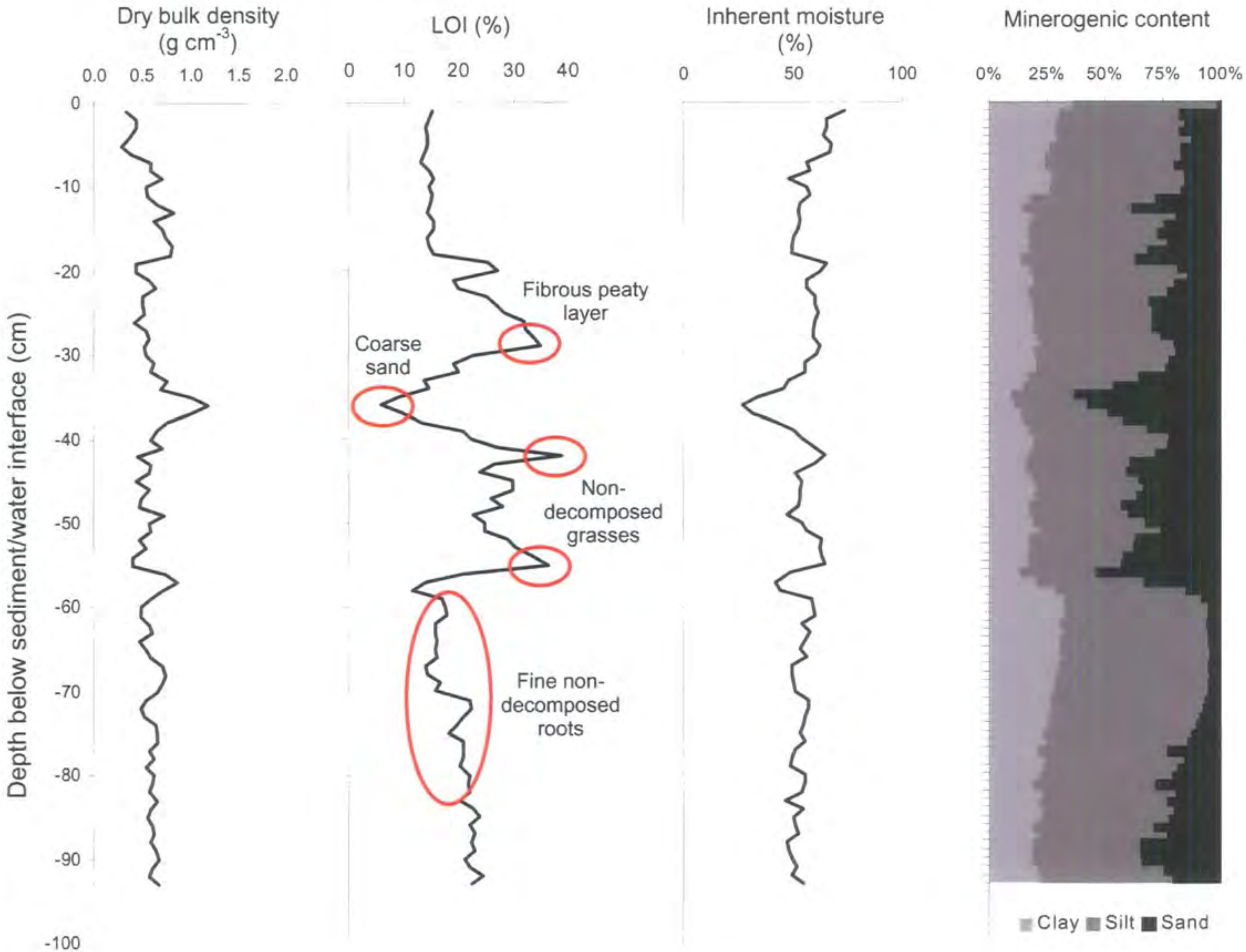


Figure 7.4 Down-core variations in dry bulk density, LOI, inherent moisture, magnetic susceptibility and minerogenic content of sediments in core 8 dated using ^{137}Cs and calibrated using ^{137}Cs fallout records for the Northern Hemisphere.

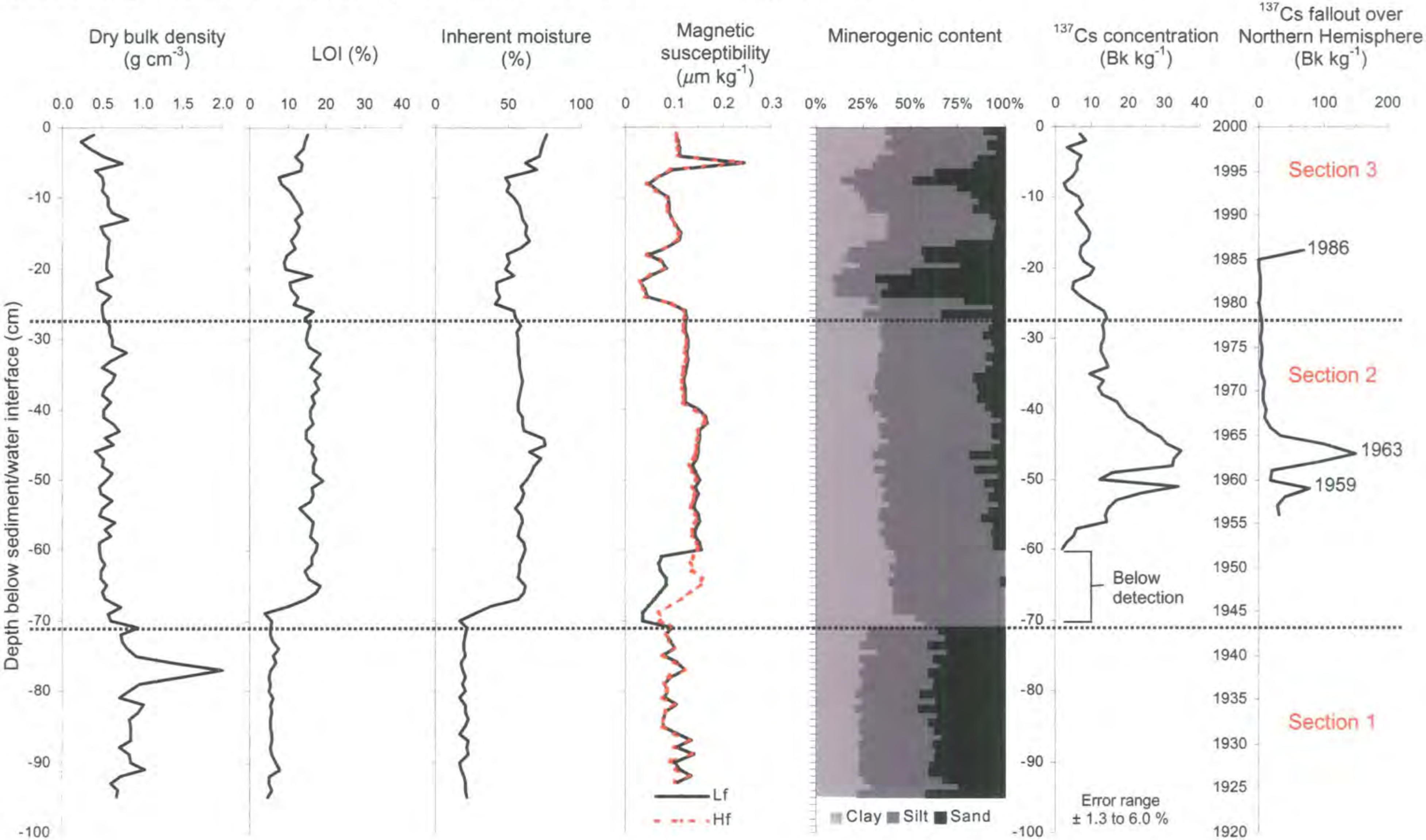


Figure 7.5 Down-core variation in dry bulk density, LOI, inherent moisture, magnetic susceptibility and minerogenic content of sediments in core 5.

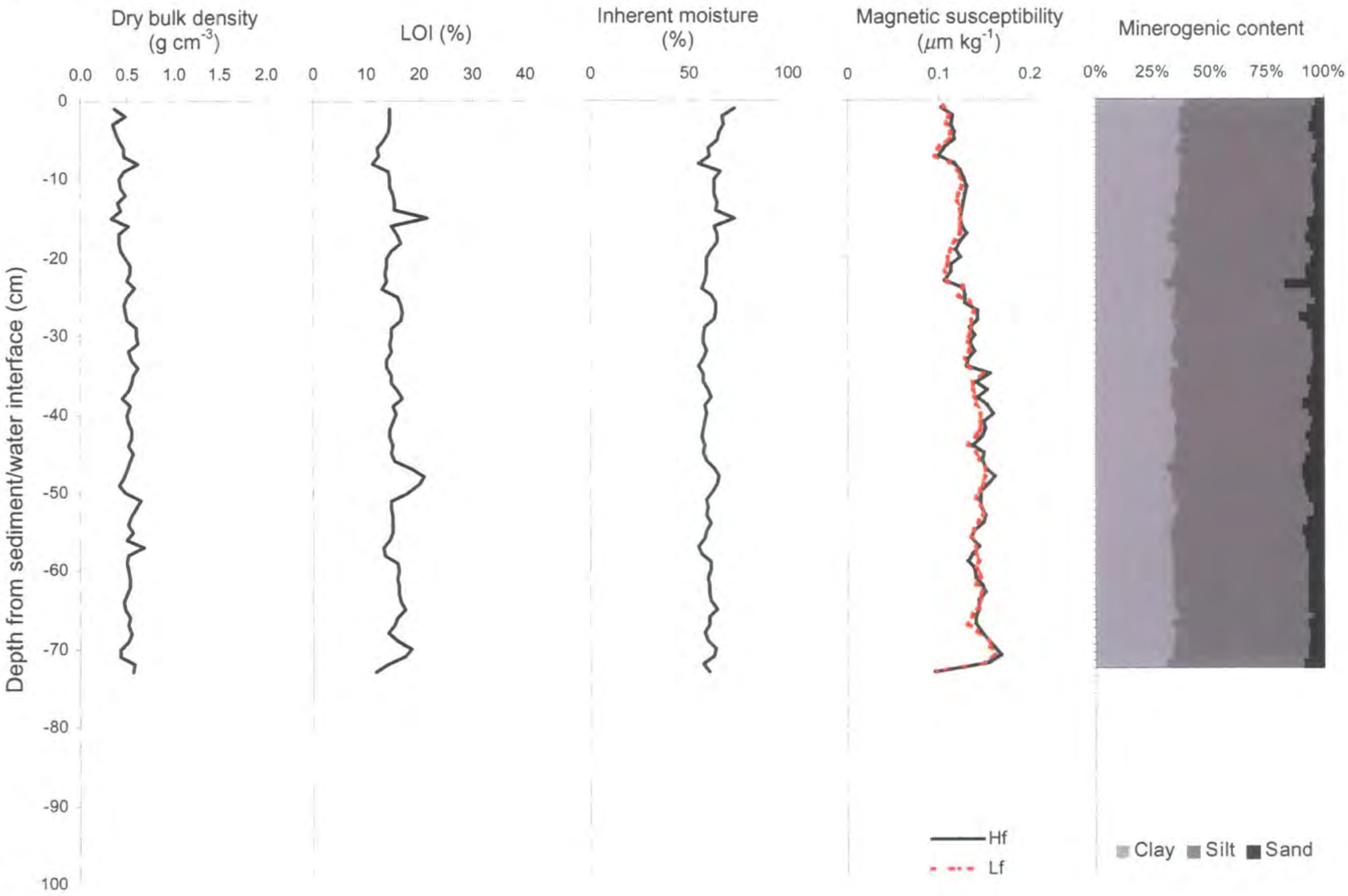


Figure 7.6 Down-core variations in dry bulk density, LOI, inherent moisture and minerogenic content of sediments in core 3.

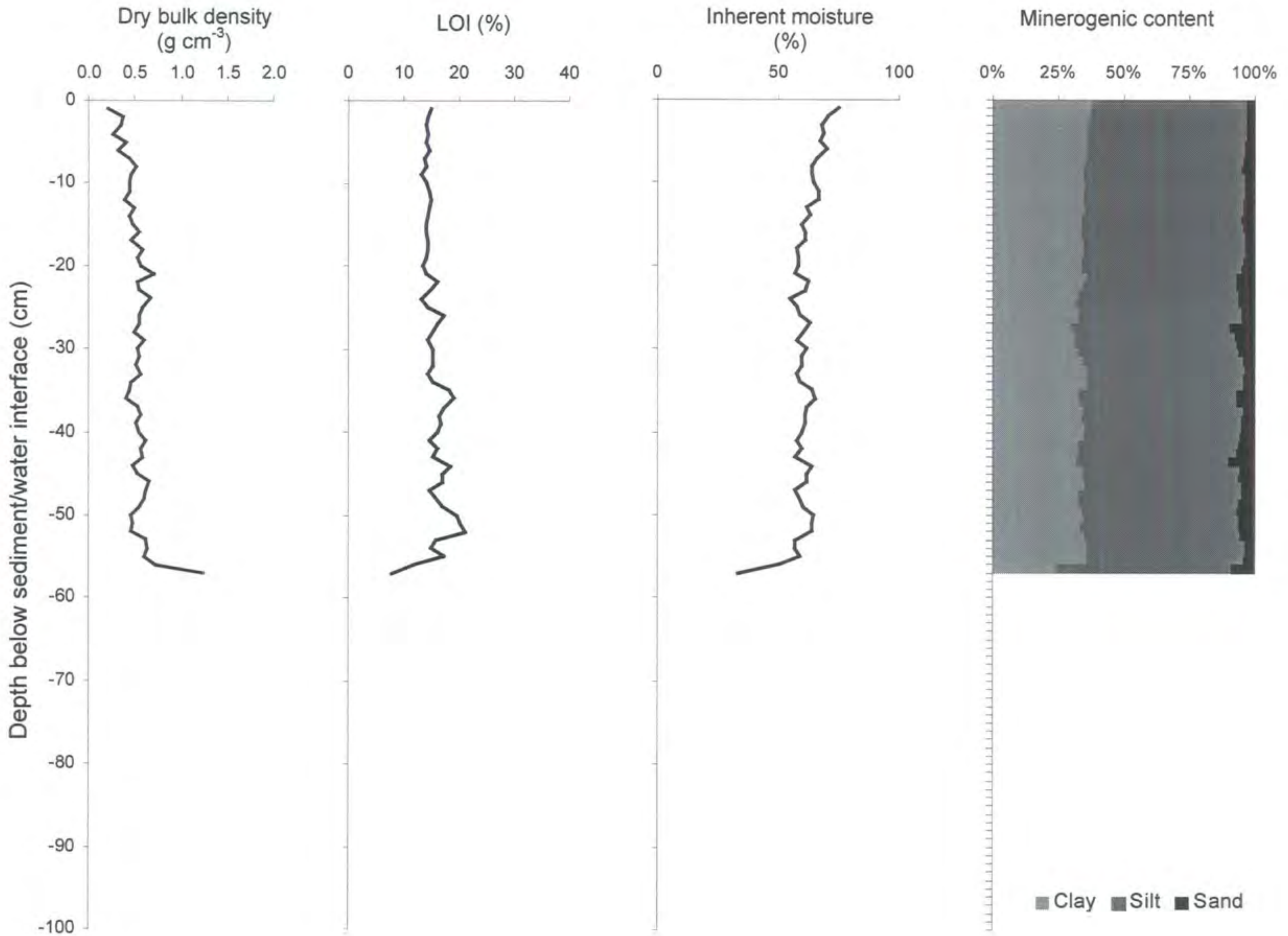
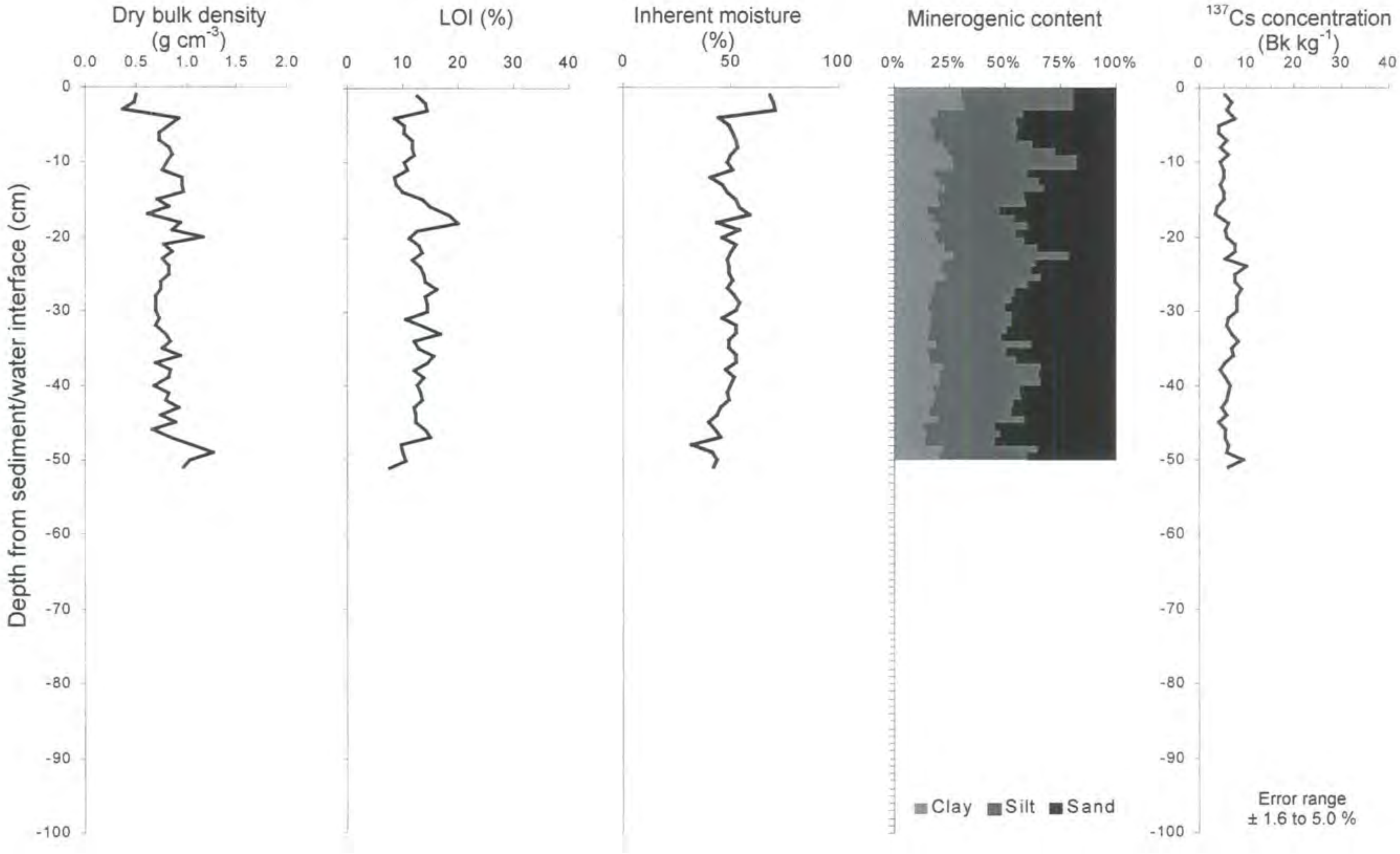


Figure 7.7 Down-core variations in dry bulk density, LOI, inherent moisture, minerogenic content and ^{137}Cs concentrations of sediments in core 6.



sand, silt and clay fractions. Cores 5 and 3 (Figure 7.5 and 7.6) show relatively uniform variations in all physical parameters down core with a fine minerogenic content of approximately 90% clay and silt. Figure 7.8 shows the depths of the sediment/water interface of all six cores and cores 3 and 5 are taken from the deepest part of the reservoir. Core 6 is taken from a similar depth but Figure 7.7 reveals a much coarser minerogenic content and evidence of variations in organic content of the sediments.

Core 6 (Figure 7.7) has a higher average sand content of >40% and distinctive fluctuations in minerogenic content down core. A peak in LOI and moisture content at 15-20 cm depth is mirrored by a decrease in bulk density indicating the presence of organics in the profile. Investigation into the location of these sediment cores in the deepest part of the reservoir has revealed a potential explanation for the distinctive characteristics of the minerogenic content of core 6. Figure 7.9 shows the core locations on an oblique air photograph of the reservoir taken during a period of draw-down in 1989. An inflow is clearly visible on the north slope of the reservoir and inset B reveals reworking of the sediment by incision on this slope. The indirect catchment that feeds Burnhope Reservoir via this pipeline is 27.9 km^2 in area. Wearhead water treatment works records the total volume of inflowing water via this pipeline but turbidity of the inflow is not monitored. Sediment inputs to the reservoir via this pipeline have been described as negligible but the inflowing water could be a potential control on sediment reworking close to the dam wall (Pattinson, 2000). Figure 7.10 shows photographs of a section of core 6 taken before extrusion. There are distinctive horizontal and shallow diagonal alternating layers of light and darker brown sediment that appear to be sand-sized particles. Due to the presence of these sloping sedimentary layers it can be tentatively suggested that the core sediments have been deposited on an incline. It is likely that the core contains reworked sediments from the slope of the reservoir. The ^{137}Cs trend for core 6 does not conform to the classic shape of fallout radionuclides and no peaks are evident in the record (Figure 4.5). The presence of low-level ^{137}Cs in the core provides further evidence that these sediments are possibly reworked. Without further sedimentary analysis the exact source of the sediment in this core cannot be determined. These stratified sediments were only present in core 6 and the remaining core stratigraphies consisted of homogenous dark brown clastic sediments with no visible sedimentary boundaries.

Cores 1, 9 and 8 (Figures 7.2, 7.3 and 7.4 respectively) are the longest records available for analysing down core trends in sedimentation. Cores 1 and 8 provide temporal records of sedimentation in Burnhope Reservoir. The results of radiometric dating of these cores using ^{137}Cs are shown in Figures 7.2 and 7.4 respectively. The

Figure 7.8 Depth of the sediment-water interface of cores in transect west to east from the input streams to dam wall.

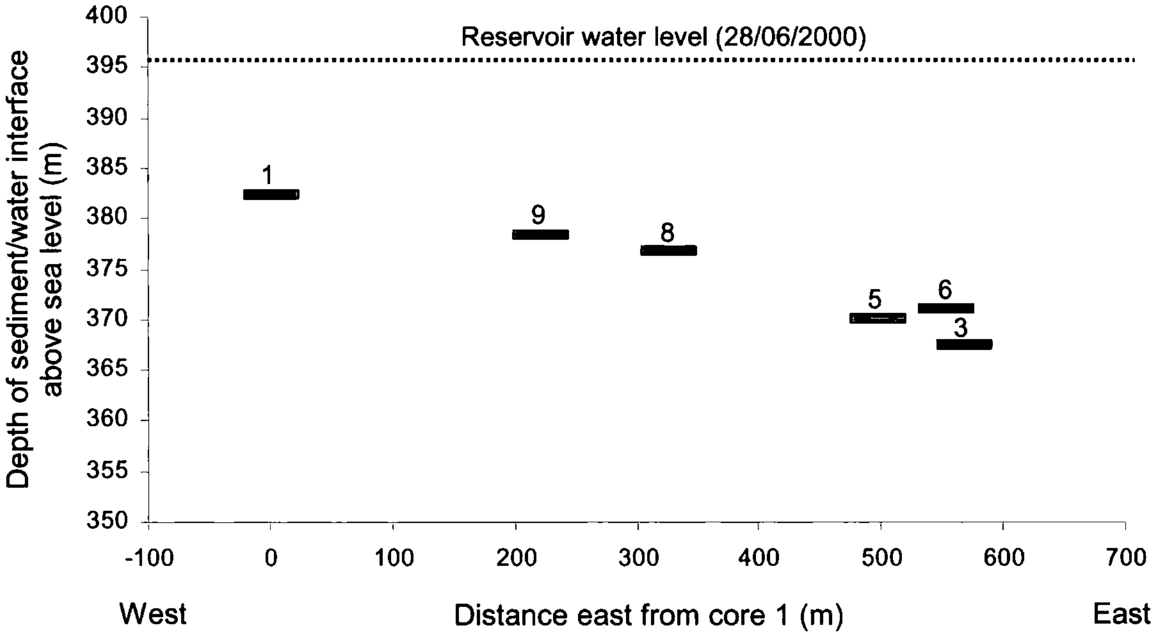


Figure 7.9 Photograph of Burnhope reservoir during a period of draw-down in 1989 showing core locations. Inset (A) highlights the location of core 9 on a bend of the old river channel. Inset (B) shows incision of sediment from inflow pipe on the north slope of reservoir.

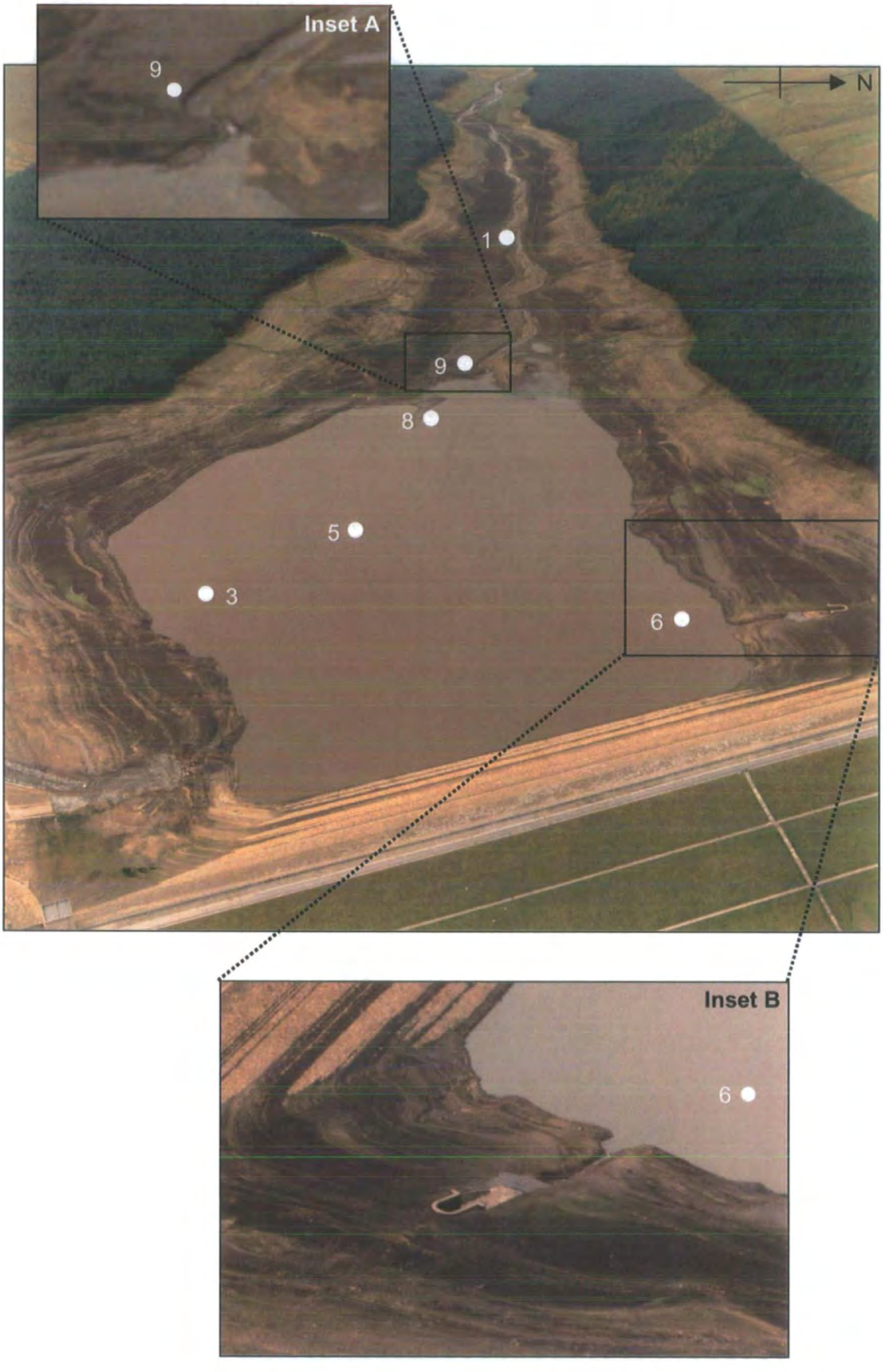


Figure 7.10 Pre-extrusion photograph of core 6.

trends in ^{137}Cs content of core sediments are compared to the record of fallout in the Northern Hemisphere after Cambray *et al.* (1987). Down-core trends in ^{137}Cs in core 1 and core 8 confirm to the classic shape relating to atmospheric fallout in the Northern Hemisphere. The 1959 and 1963 peaks in fallout in the Northern Hemisphere closely correspond to those measured in core sediments. The 1986 Chernobyl peak in the fallout record is not evident in the core sediments. The spatial distribution of Chernobyl ^{137}Cs fallout in upland Britain was highly variable (Higgitt *et al.*, 1993). Based on radiometric dating, average sedimentation rates of 0.7 and 1.24 cm yr^{-1} have been calculated for core 1 and core 8 respectively. Peak ^{137}Cs concentrations recorded in core 8 are twice those measured in core 1. These differences could reflect disparities between the sedimentary environments under which the sediments were deposited. Finer sediment particles remain in suspension and are moved closer to the dam wall resulting in particle enrichment of ^{137}Cs in deep-water sediments (cf. Foster *et al.*, 1994). This is an example of the influence of particle size on ^{137}Cs concentrations in sediments. Figure 7.9 shows that core 1 was retrieved from a relatively shallow section of the proximal limb of the reservoir that is prone to exposure when reservoir levels fall. Core 8 is located in the main body of the reservoir, a deeper site that is more susceptible to sediment focussing than sediment reworking during minor fluctuations in reservoir level. Analysis of the physical parameters of core 1 (Figure 7.2) reveals minor fluctuations in dry bulk density that mirror more pronounced variations in LOI and inherent moisture content. Minor peaks in LOI and moisture content can be interpreted as layers with a higher organic content. The particle size record is dominated by two peaks in sand-sized sediment between 10-20 and 30-40 cm down core. Based on the average sedimentation rate of 0.7 cm yr^{-1} the layers date from 1975 to 1983 and from 1951 to 1957, respectively.

Figure 7.4 shows core 8 split into three sections for ease of description of the physical parameters. The minerogenic composition of sediments shows distinct variations in the content of silt, sand and clay particles down core. Section 1 has uniform minerogenic sediments with negligible variation between the sand, silt and clay content. There is a sharp upper contact between sections 1 and 2 where the sand composition of the sediments varies from 0 to 40% within 1 cm of accumulation. LOI and inherent moisture content follow a similar trend categorising the sediments in section 3 as different from the layers above. Bulk density measurements increase three fold forming a peak of 1.8 g cm^{-3} at 78 cm depth. Based on the average sedimentation rate of 1.24 cm yr^{-1}, the peak in dry bulk density is dated to around 1936, which is the year Burnhope Reservoir was impounded and sections of the reservoir basin were compacted. Section 3 can therefore be interpreted as made ground. The minerogenic content of section 2 is reasonably uniform in nature, silt (~50%) with clay (~30%) and sand (<20%). Section 3 at the top of the core is the coarsest with distinct peaks in sand-sized particles representing up to 70% of the minerogenic content of sediments. Again if a uniform sedimentation rate of 1.24 cm yr^1 is assumed, these coarse-grained layers have been deposited from 1977 to 2000.

Located between core 1 and core 8, core 9 (Figure 7.3) shows the most dynamic down core trends in LOI, with values ranging from <5 to >35% organics. The LOI plot is annotated from notes taken during extrusion that aid interpretation of the distinctive variation in organic content of this core. As the notes suggest, towards the base of the core the sediments contain fine organic roots that are potentially those non-decomposed grasses that form the overlying layer between -40 and -60 cm. A layer of coarse sand results in a sudden decrease in LOI from >35% to <5% in only 5 cm of sediment. A fibrous peaty layer located around –30 cm forms the surface of what could tentatively be described as an old river terrace. Core 9 is located on a bend of the old river channel (see inset A on Figure 7.9) that appears to be covered in fine minerogenic sediment that has been deposited since impoundment.

From analysis of down-core variations in physical and radiometric sedimentological parameters of six cores, it has been possible to identify spatial variations in sedimentation in the Burnhope Reservoir basin. An overall fining of sediment from west to east has been observed from the input streams to the dam, as water depth increases. This is with the exception of core 6 that is possibly sampled from sediments reworked by the inflow. Cores 1 and 8 have distinctive layers of coarse-grained sediment that have been dated using ^{137}Cs. Both cores have coarse-grained deposits dated from the mid 1970s while core 1 has an earlier layer dated from 1950 to 1957.

The next section of the chapter investigates potential controls on the deposition of the observed coarse-grained layers, concentrating on variations in the hydroclimate and considering the hypothesis that coarse-grained influxes are most likely connected to high-magnitude, low-frequency events.

7.3 Analysis of historical rainfall records

Monthly and annual rainfall totals were calculated from daily records from Wearhead Water Treatment Works at Burnhope Reservoir for the period 1936 to 1998. The number of days recording rainfall per annum was also determined for the same period.

Graphs of variations in both monthly and annual rainfall totals and the number of days recording rainfall are used to analyse the long-term rainfall record. Figure 7.11 highlights the variation in annual rainfall totals in the long-term rainfall series (1936 to 1998). The five-year moving average shows a gradual decrease in annual rainfall totals for the twenty-year period from 1950 to 1970 when there is a decline until the mid 1970s. The twenty-year period from 1975 to 1995 sees a steady increase in annual rainfall totals. The mean annual precipitation total for the Burnhope catchment (400-746 m O.D) is 1287 mm but varies considerably, with 897.4 mm and 1786.7 mm recorded for 1971 and 1954, respectively. These values of mean annual rainfall are slightly lower than others monitored in the North Pennines. Smithson (1985) reports mean totals of 2010 mm for Moor House (290-848 m O.D) in upper Teesdale between 1941-70. These higher values were recorded on Teesdale escarpment and highlight the influence of altitude on precipitation totals within the region.

Mean monthly rainfall totals recorded for the 67-year period are shown in Figure 7.12. The months October to March record average totals greater than 100 mm per month, while the months April to September record less than 100 mm per month. For ease of description, the months October to March and April to September will be referred to as the winter-centred and summer-centred periods respectively. Figure 7.13 compares the total mean rainfall for the winter and summer-centred periods from 1936 to 1998. From the mid 1940s to 1976 there appears to be consistency between the winter and summer-centred five year moving average trendlines. From 1976 onwards there is a diverging trend apparent between the winter-centred and summer-centred rainfall totals, with a large increase in winter and a gradual decrease in summer values. These trends in the Burnhope rainfall data are consistent with those recorded elsewhere in the United Kingdom of wetter winters and drier summers (Jones and Conway, 1997; Marsh and Sanderson, 1997). Three of the five wettest winters since the 1766-1777 period were recorded in 1989-1990, 1993-1994 and 1994-1995 (Jones and Conway, 1997).

Further analysis into temporal variations in rainfall involved calculation of the number of days recording rainfall from 1936 to 1998. Figure 7.14A highlights trends in the average number of days of rainfall divided into three sections for ease of description. Section 1 shows a gradual decrease in the number of days of rainfall between 1950 and the early 1970s, while section 2 records an increase in the number of days recording rainfall between the mid 1970s and early 1980s. Section 3 is characterised by a significant decrease in number of days of rainfall, recording an average of 200 days in 1995, the lowest number on record.

Figure 7.11 Mean annual rainfall for the Burnhope catchment for the period 1936-1998.

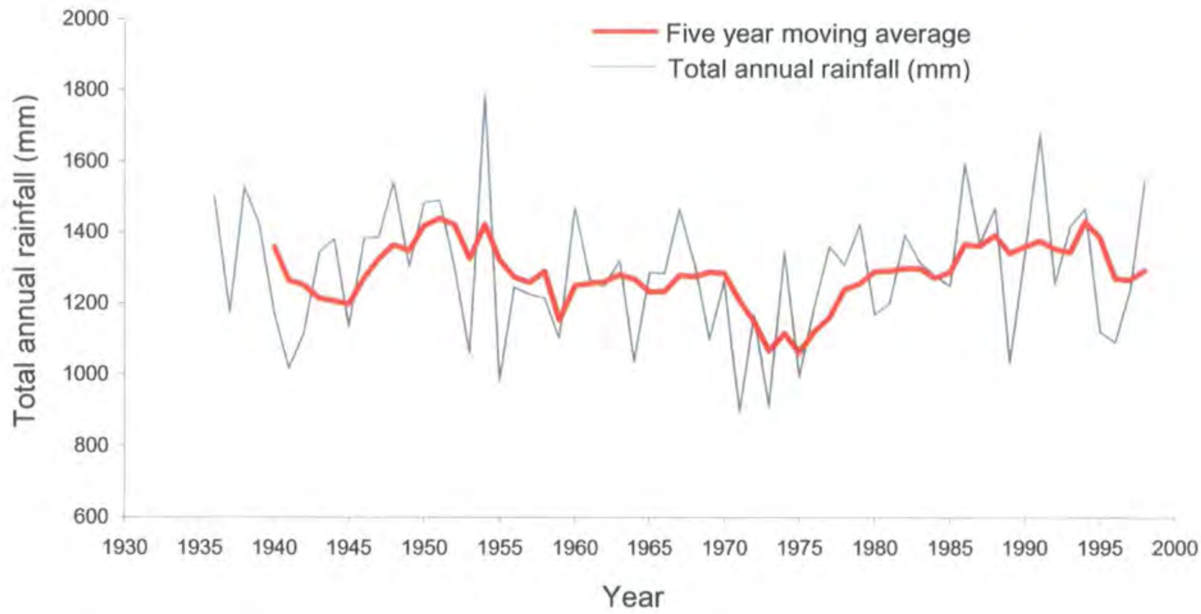


Figure 7.12 Mean monthly rainfall totals recorded between 1936-1998.

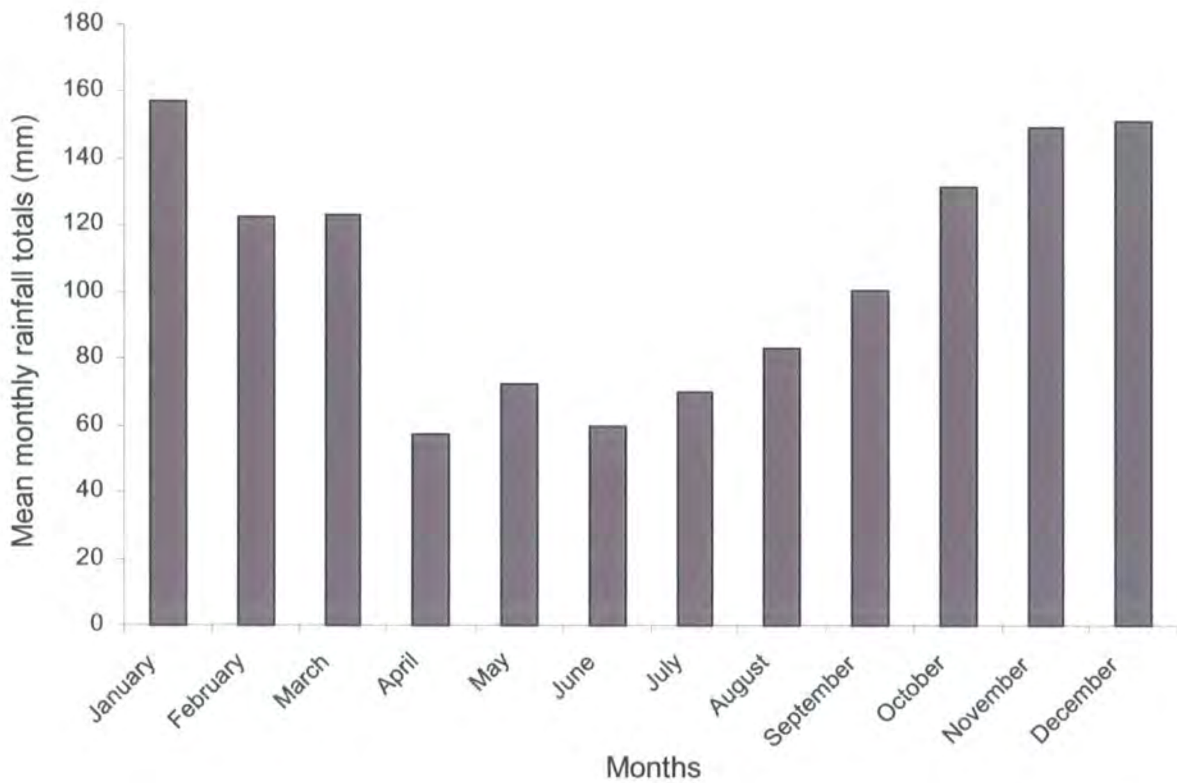


Figure 7.13 Comparison between total mean rainfall for the months October to March and April to September 1936-1998.

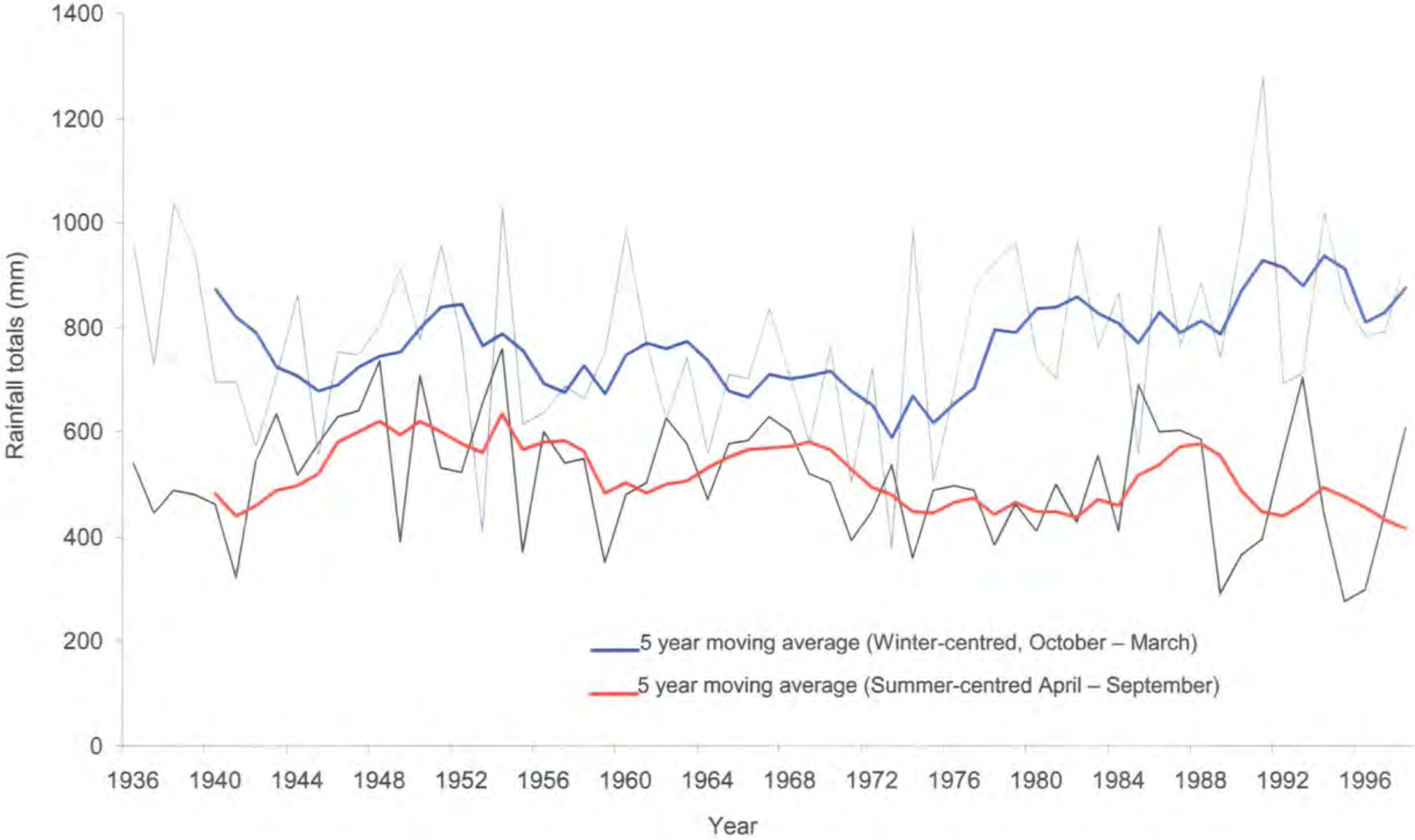


Figure 7.14 Number of days recording rainfall (A) from 1936 to 1998 and (B) during the winter and summer periods from 1977 to 1998.

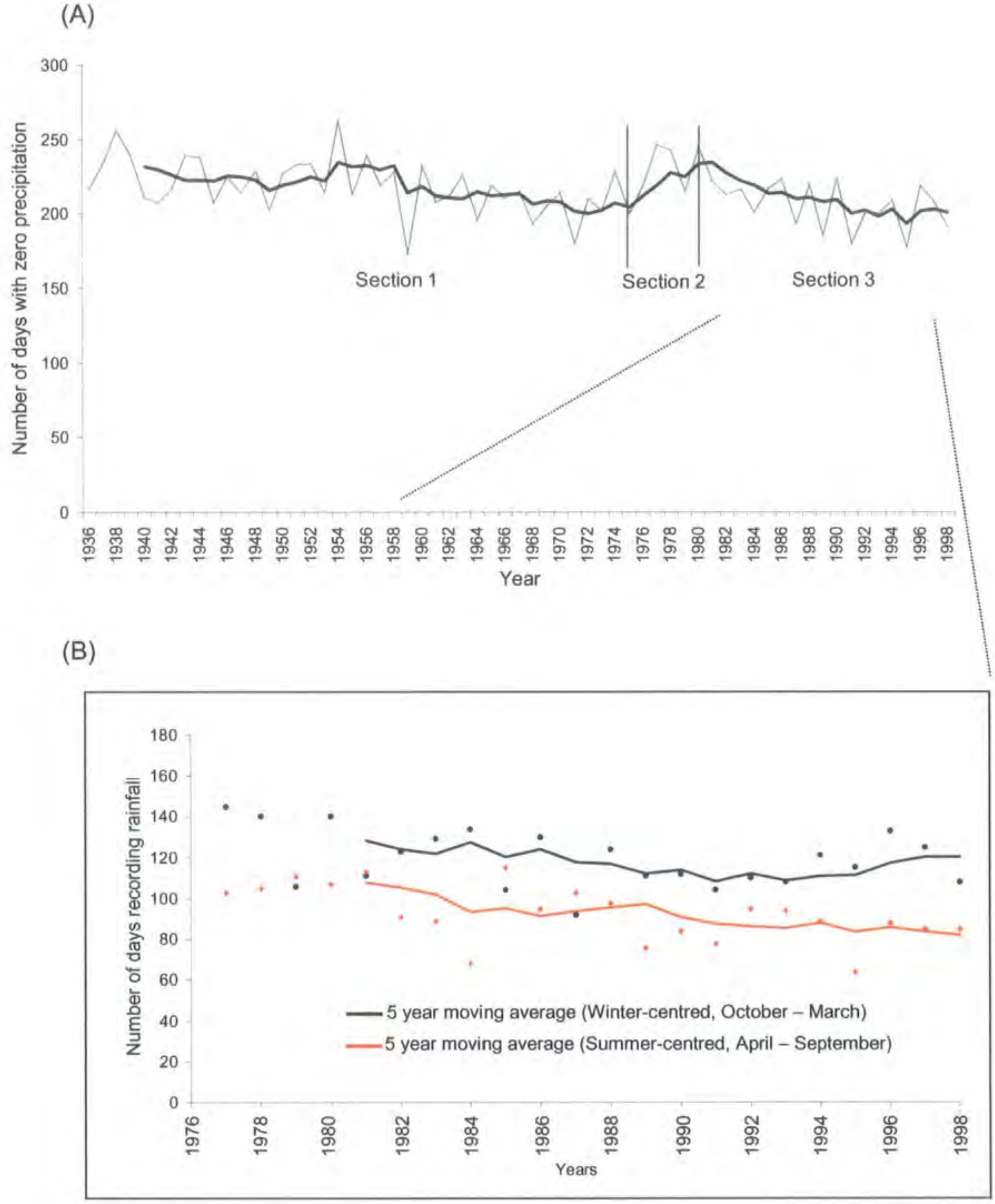


Figure 7.14B shows the period from 1976 more closely, comparing the number of days recording rainfall for the summer-centred and winter-centred months from 1976 to 1998. The five-year moving averages for the winter-centred and summer-centred periods show a parallel decreasing trend. When this tendency is compared to the annual totals in Figure 7.11, a negative relationship exists between the number of days recording rainfall for the winter-centred period in section 3 and annual rainfall totals. This indicates that either the rainfall intensity has increased or the duration of individual events has increased but the frequency of these events has decreased during the months of the winter-centred period. Osborn *et al.* (2000) report that the intensity distribution of daily precipitation amounts in the UK had changed over the period 1961-1995, becoming more intense in winter and less intense in the summer. In terms of their relative contributions to total winter precipitation, there has been a decline in light and medium events and an increase in the heaviest events (Osborn *et al.*, 2000). This change has been noted as fairly uniform across the whole of the UK. The reverse trend has been reported for summer rainfall over the same period with a decline in the proportion of seasonal totals being provided by the heaviest events (Osborn *et al.*, 2000). Despite this general trend there are still reports of significant convective thunderstorms occurring over upland regions of Scotland (McEwen, 1989a), Wales (Newson, 1980a) and Northern England (Carling, 1986a & b) over this period.

It is difficult to assume that a trend in days recording rainfall represents a transition to a drier or wetter period. This is due to the uncertainty surrounding the number of days recording precipitation as a result of snowfall. Temperature controls the nature of precipitation and if winters become warmer the precipitation that would have fallen as snow would then be recorded as rainfall. Temperature records for Burnhope are only available for 1992-1998, which is insufficient for investigation into the exact courses of these historical rainfall trends. On the basis of a negative relationship between days of rainfall and total rainfall and UK trends reported by Osborn *et al.* (2000) it is likely that rainfall intensity has increased from 1976 to 1998.

7.4 Trends in particle size and rainfall records

Figure 7.15 and 7.16 show the down-core variations in particle size calibrated using ^{137}Cs and mean monthly rainfall totals for cores 1 and 8 respectively. In both cores the occurrence of coarse-grained layers in section 3 correspond to the diverging trend in mean monthly rainfall totals recorded from 1975 to 1998. Figure 7.15 reveals a second coarse-grained peak in section 1 that relates to the reversal of the rainfall signature.

Figure 7.15 Comparison between minerogenic content of core 1 (A) and (B) mean monthly rainfall for the period October to March and April to September from 1936 to 1998, (C) ^{137}Cs chronology of core sediments and (D) ^{137}Cs fallout recorded in the Northern Hemisphere from 1958 to 1986.

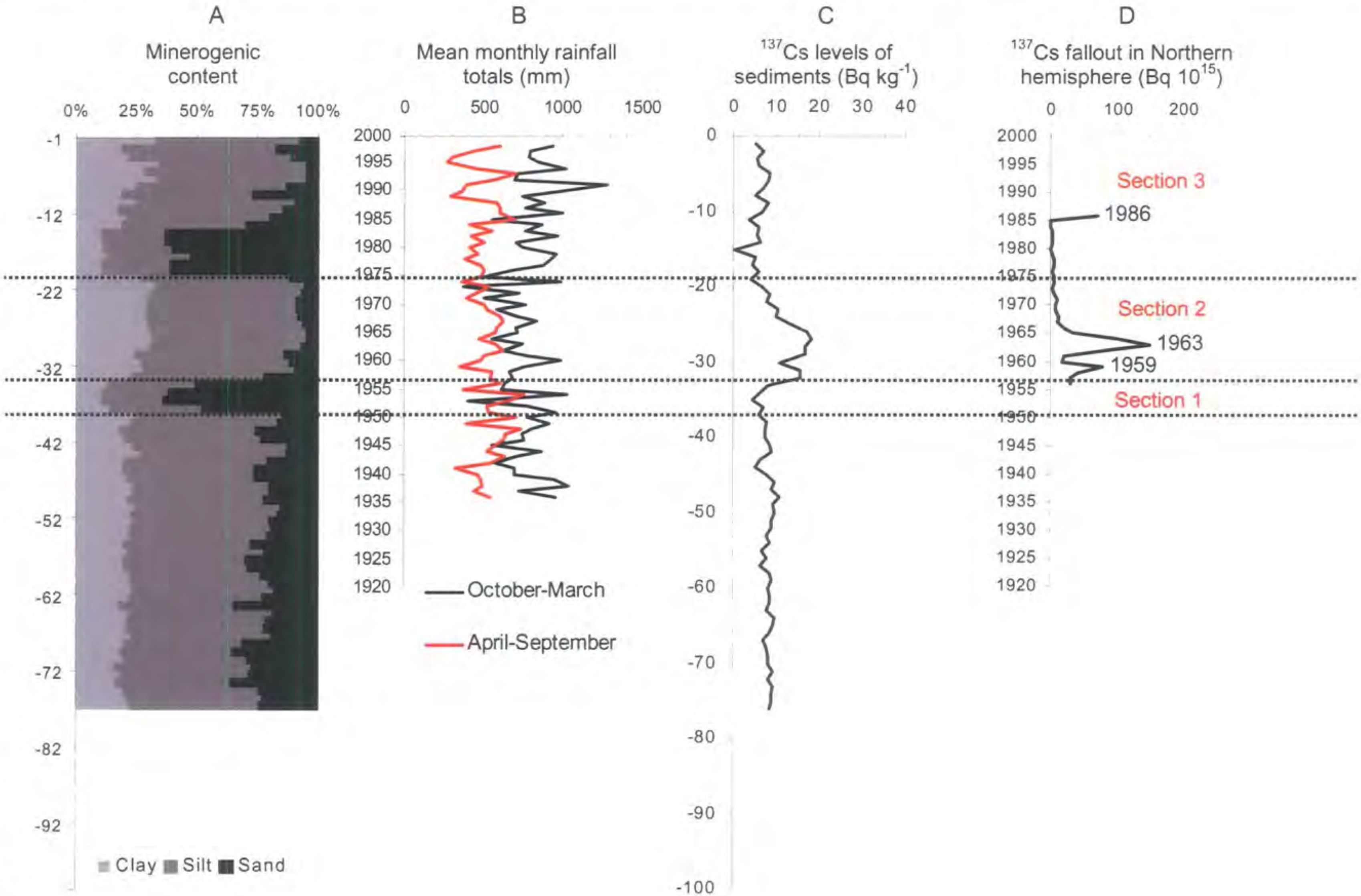
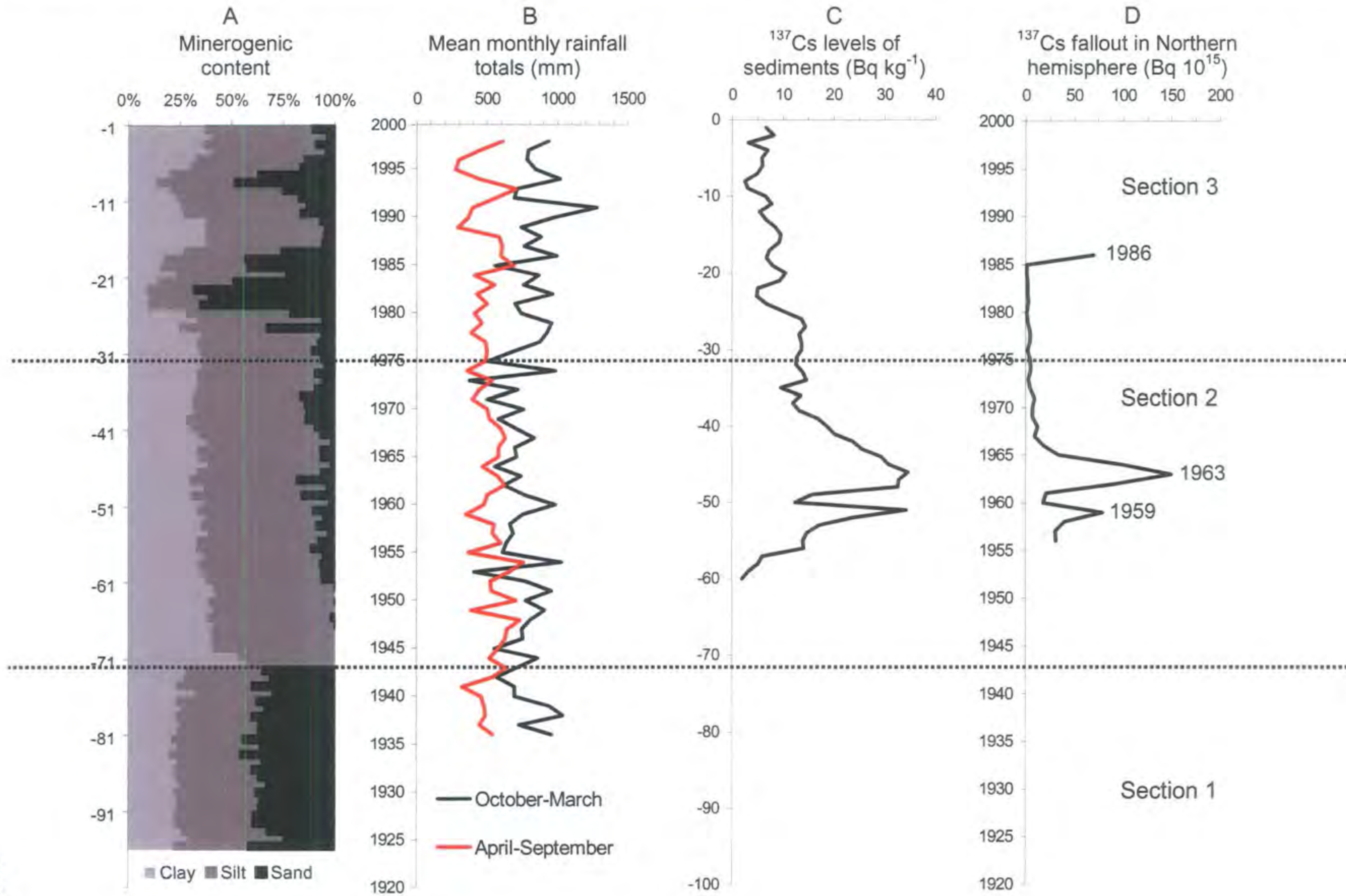


Figure 7.16 Comparison between minerogenic content of core 8 (A) and (B) mean monthly rainfall for the period October to March and April to September from 1936 to 1998, (C) ^{137}Cs chronology of core sediments and (D) ^{137}Cs fallout recorded in the Northern Hemisphere from 1958 to 1986.



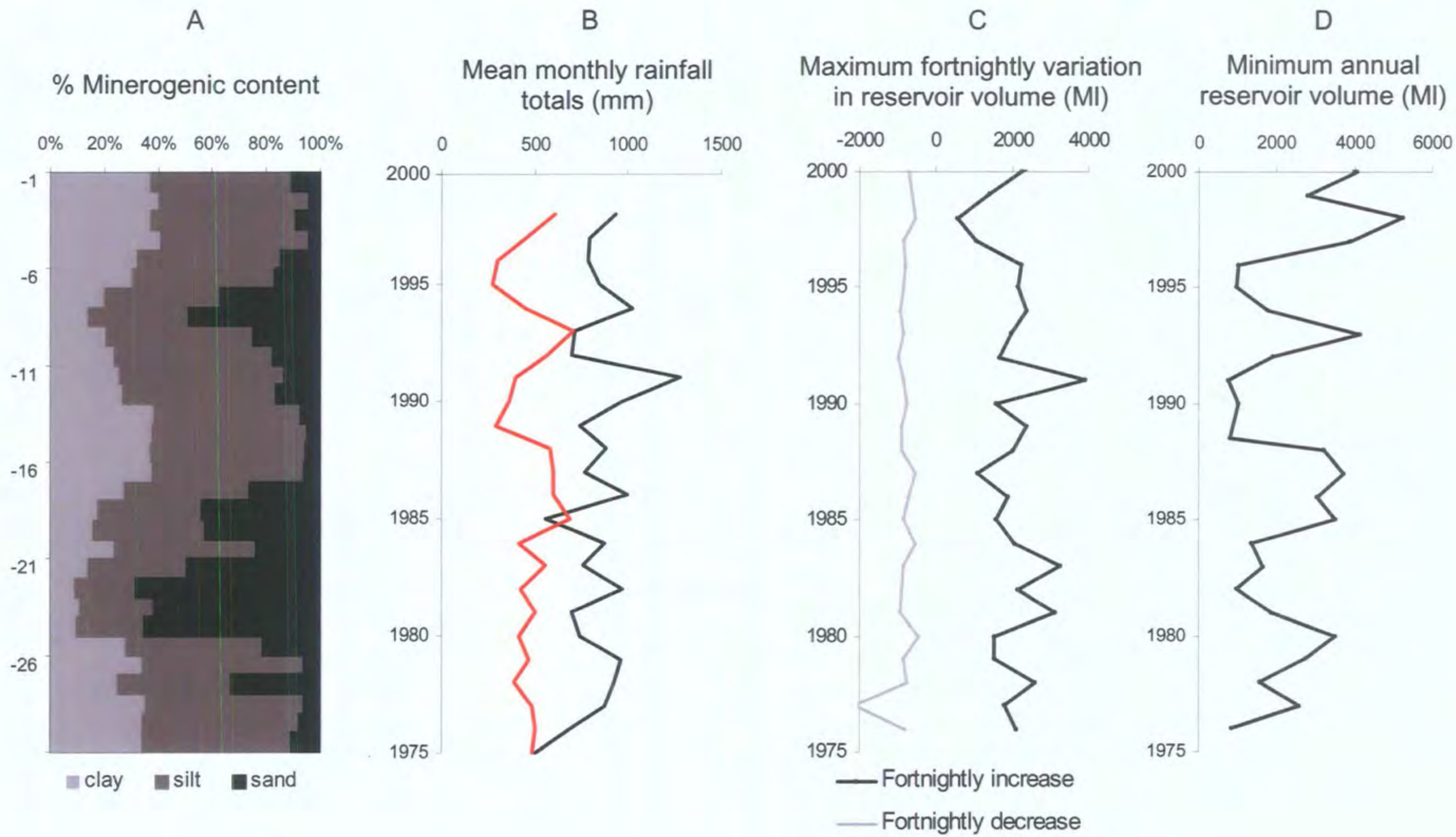
The second lowest winter rainfall total on record (406 mm) fell between October and March 1953 followed by the largest total summer rainfall on record (758 mm) falling between April and September 1954. Periods of hydroclimatic variability appear to correspond to influxes of coarse-grained sediment.

The dynamics of sediment delivery and movement within the reservoir is in part dependent on reservoir water level variations. The nature of sedimentary environments in the reservoir varies depending on potential exposure during a dawn draw event. Sections of the reservoir can change from being mainly areas susceptible to deposition at high water levels to active source areas due to sediment reworking during draw down.

7.4.1 Trends in reservoir levels in comparison to rainfall totals and the minerogenic content of core sediments

Northumbrian Water Limited recorded reservoir levels on a fortnightly basis from 1976 to 2000. Although reservoir water levels are controlled by the water company, climate is the primary control on the demand for water in Burnhope Reservoir and therefore relatively close relationships between variations in rainfall and water levels are expected. When considering the possible controls on the deposition of coarse-grained sediment fluxes to the reservoir as identified in Section 7.3 it is probable that high-magnitude, low-frequency events are responsible, which could be recorded as rapid increases in reservoir water level. Figure 7.17 shows Section 3 of profiles A and B from Figure 7.16 in more detail and includes profiles C and D which show the annual trends in maximum rise and fall of reservoir levels over a fortnightly period and the minimum recorded level per annum. During the periods of maximum variation between summer and winter rainfall periods in the early 1980s and 1990s, maximum fortnightly variations in reservoir level are recorded. Figure 7.17 shows the trend in minimum annual reservoir levels corresponding to the years with lowest summer rainfall (April to September). These drought periods in the early and late 1980s and early 1990s are synonymous with peaks in winter rainfall (B) and maximum fortnightly variations in reservoir level (C) most notably in the early 1990s. Based on ^{137}Cs chronologies of core sediments and the assumption of an average sedimentation rate the onset of the two sand-dominated layers (>50%) in the upper section of core 8 (Figure 7.16 & 7.17) correspond to the drought periods of the late 1980s and early 1990s. These periods are also characterised by lowest recorded reservoir levels and periods of maximum variation in rising reservoir levels. Core 8 is located at the margin of inundation at the point of maximum down-draw. For this reason the sediment record is susceptible to

Figure 7.17 Comparison between (A) minerogenic content of core 8 (1- 30 cm) and (B) Mean monthly rainfall totals for the period October to March and April to September, 1975 to 1998, (C) maximum fortnightly variations in reservoir volume from 1976 to 2000 and (D) minimum reservoir volume recorded from 1976 to 2000.



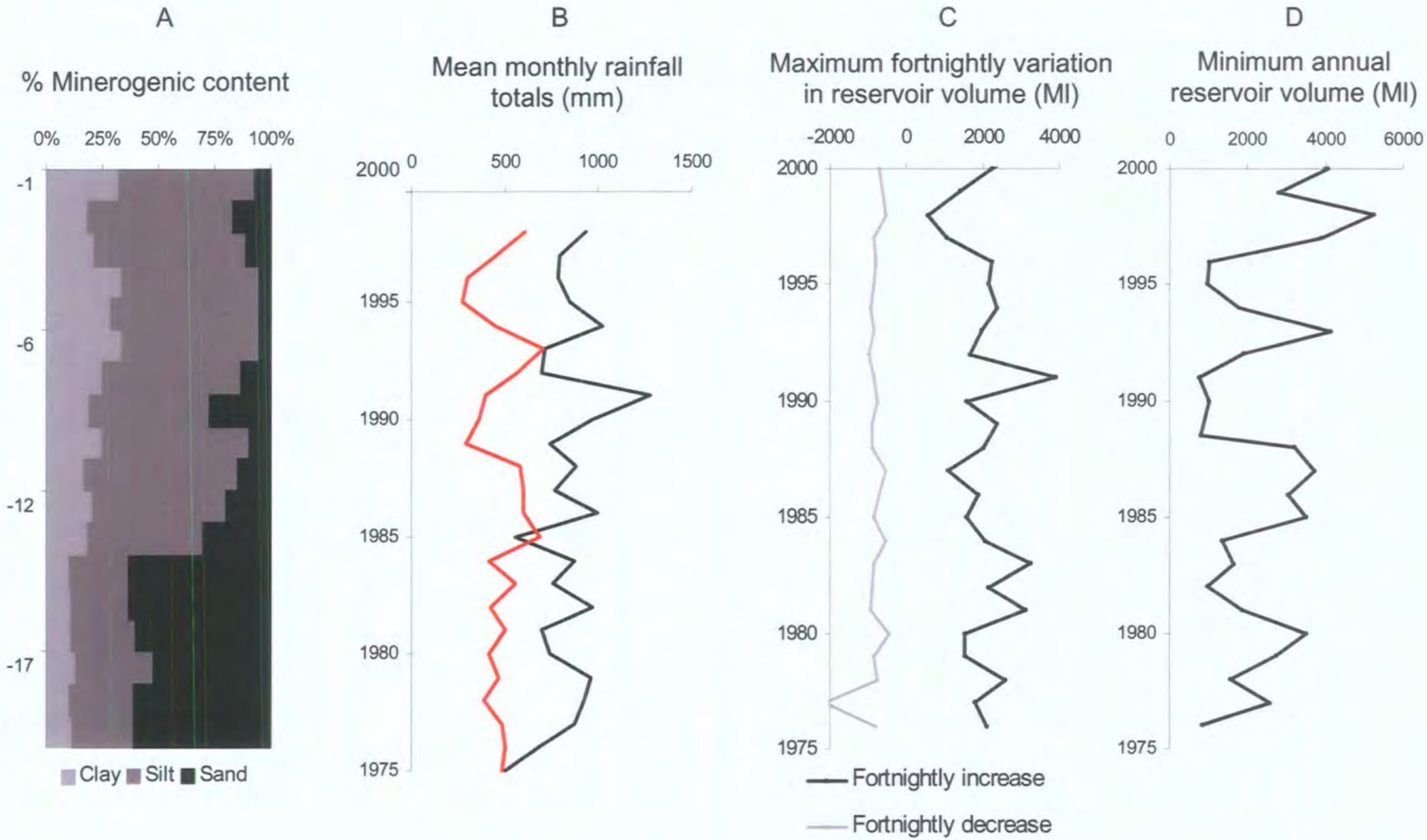
maximum variations in reservoir levels in terms of sediment reworking and is also a likely location for catchment sediment deposition from inflows via the old channel during draw down periods.

Figure 7.18 shows section 3 of profiles A and B from Figure 7.15 in more detail and includes profiles C and D showing variations in reservoir water levels. The correlation between coarse-grained layers and reservoir levels varies on the basis of exposure of the proximal section of the reservoir during draw-down. Sediment deposition in this location will occur when reservoir levels are higher and this section of the reservoir is sufficiently inundated. It is therefore expected that during periods of maximum divergence between winter and summer rainfall and higher minimum annual reservoir levels coarse-grained sediments will be deposited.

The potential links between the onset of increased sedimentation in the reservoir cores and trends in rainfall and reservoir level fluctuation can be interpreted in two ways. The first is concerned with the potential effects that diverging rainfall totals have on the sediment transfer system within the catchment. Long spells of low rainfall during the summer period reduce sediment transport capacity resulting in temporary storage of fluvial sediments within the catchment. Brief periods of mass sediment transfer will occur during the first few significant rainfall events, when sediment stores are re-activated. Once a sediment source is activated it may remain active for an extended period of time supplying sediment long after the initial trigger event has passed. Single events may deliver substantial quantities of coarse-grained sediment to the reservoir. Therefore although average sedimentation rates have been assigned to core 1 and 8 it is possible that annual accumulation rates will vary.

The second interpretation considers the large magnitude increases in reservoir level over short timescales that are likely to result in flushing of sediment from the proximal delta, and reservoir sides downstream towards the dam. This process will be most effective during periods when the reservoir levels are lowest. Oblique photographs of the reservoir taken in 1989 (Figure 7.9), when levels were only 6.5% of the maximum, provide evidence of incision of the pre-impoundment channel down to its gravel and boulder bed. Incision and flushing will have reworked channel fill sediments, re-mobilising, transferring and re-depositing material in the deeper parts of the reservoir that remain inundated during draw down. Further evidence for this sediment reworking is provided by the presence of ^{137}Cs in the core record after 1986.

Figure 7.18 Comparison between (A) minerogenic content of core 1 (1-19 cm) and (B) Mean monthly rainfall totals for the period October to March and April to September, 1975 to 1998, (C) maximum fortnightly variations in reservoir volume from 1976 to 2000 and (D) minimum reservoir volume recorded from 1976 to 2000.



Linking variations in coarse-grained sediments within the reservoir and the recent variations in the winter and summer-centred rainfall patterns and reservoir levels is complicated. Issues of reservoir sediment dynamics; sediment availability and supply; and reservoir operations must be considered if an understanding of how sedimentation in Burnhope Reservoir has changed in recent decades. Records of reservoir levels provide valuable information on timescales of water depth fluctuations and it appears that mean monthly rainfall and reservoir levels do correspond to periods of coarser sedimentation in Burnhope Reservoir. However, the source of the sediments cannot be easily determined and further research into sediment availability and supply during drier periods is essential if the effects of changes in the hydroclimate on sediment transfer in this drainage basin are to be fully understood.

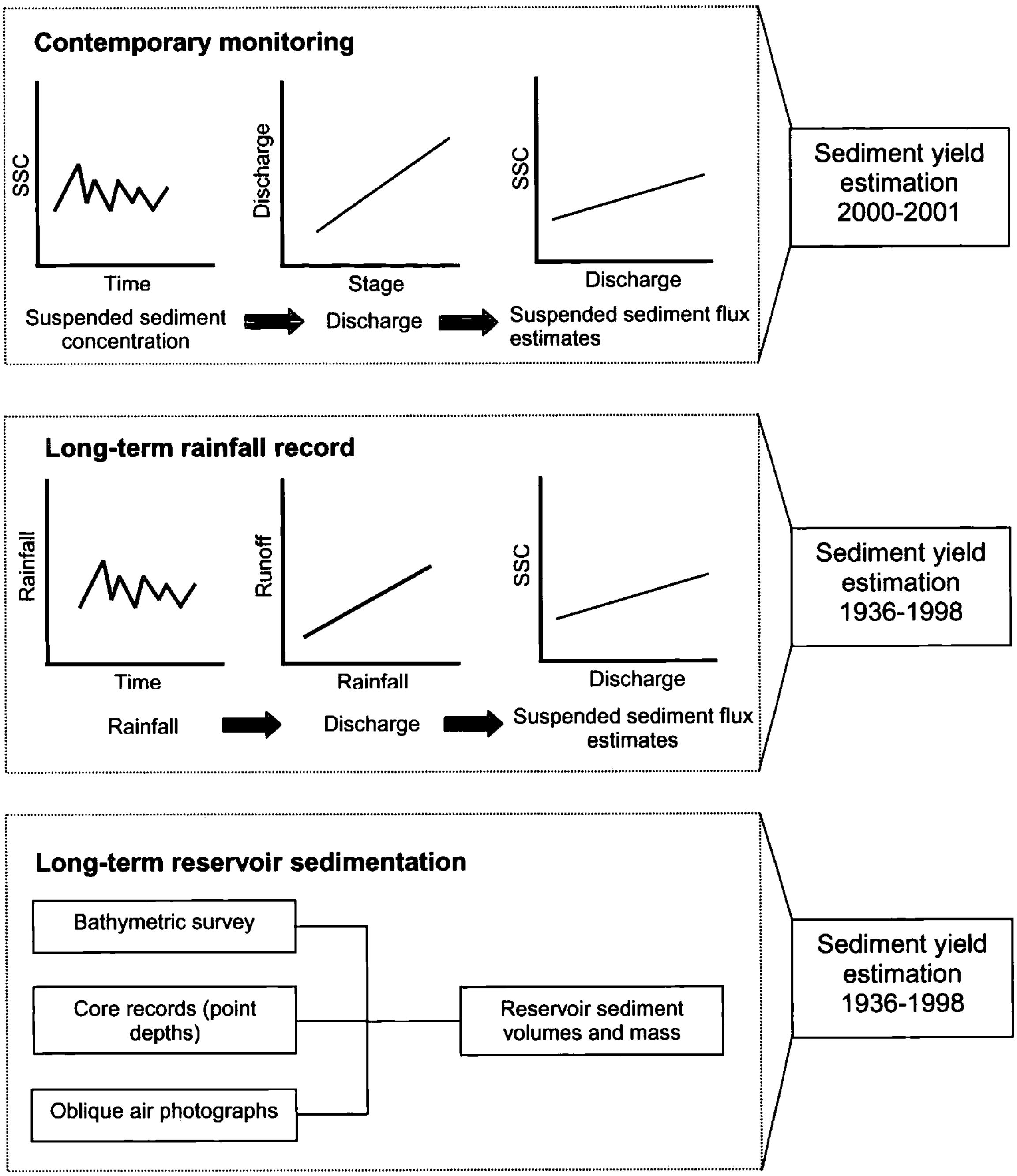
7.5 Estimation of long-term sediment yields

Suspended sediment yields have been estimated for the Burnhope and Langtae catchments using three methods. Firstly, contemporary suspended sediment loads were estimated from monitored data as discussed in Chapter 5. Secondly historical daily rainfall data from the Burnhope catchment for the 1936 to 1998 period is used together with contemporary rainfall-runoff and suspended sediment rating relationships to produce annual sediment yields. Finally, long-term reservoir sedimentation is used together with bulk density estimates and the ^{137}Cs chronology of core sediments, to calculate volume and mass of reservoir sediment from 1936 to 2000. Figure 7.19 is a schematic diagram illustrating the methods employed in determining sediment yields for the Burnhope and Langtae catchments.

7.5.1 Estimation of long-term sediment yields from historical rainfall data

Prior to this study, Burnhope and Langtae were un-gauged catchments and the only environmental data records available were daily rainfall totals (mm). Annual sediment yields are estimated from daily rainfall totals using a combination of rainfall-runoff correlations and sediment rating relationships for the Burnhope and Langtae catchments. Runoff for the study period was calculated for both catchments based on discharge measurements and runoff correlated with rainfall to produce runoff coefficients. In order to assess the possibility for estimating runoff from daily rainfall records from 1936 to 1998 using the contemporary regression equation, it was

Figure 7.19 Schematic diagram of the methods employed in determining sediment yields for the Burnhope and Langtae catchments.



necessary to consider the direct (precipitation) and indirect controls (land use change) on catchment runoff. Information provided by local land owners and farmers indicates that there has been negligible change in land use practices in the Langtae and Burnhope catchments over the 67 year period and that rainfall records are available on a daily basis (1936 to 1998). It is therefore assumed, for the purpose of this study, that the relationship between rainfall and runoff has remained relatively constant. Daily discharge values were determined from these runoff estimates and the contemporary sediment rating relationships for Burnhope and Langtae systems used to determine suspended sediment concentrations from daily discharges for the period 1936 to 2000. The assumption is made that the relationship between suspended sediment concentration and discharge had remained constant throughout the 67-year record.

Table 7.1 compares sediment yield estimations from contemporary monitoring based on rating curves using both the general and seasonal data sets with those calculated from the mean annual historical rainfall record. The results of rainfall-based sediment yields for the Burnhope catchment are slight underestimates of those determined from contemporary monitoring using both general and seasonal rating curves. The yields estimated from rainfall for the Langtae catchment are four times greater than those determined from monitoring. These large discrepancies between the methods of sediment yield estimation can be explained by considering the assumptions inherent in predicting historical sediment loads from historical daily rainfall records based on contemporary rainfall/runoff and sediment rating relationships.

The critical issues concern in the conversion of historical daily rainfall totals into daily runoff and discharge. The load estimates in Table 7.1 are based on daily runoff (m^3) converted to discharge ($m^3 s^{-1}$) averaged over a 24–hour period. In reality there are fluctuations in daily discharge over a 24-hour period and this is evident from storm event analysis (Figure 6.11) discussed in Chapter 6, Section 6.7. For example, during event BS02, discharge increased from 0.8 to 2.5 $m^3 s^{-1}$ in 6 hours and from this peak back to pre-event flow within 16 hours of the onset of the event. The modal duration of rainfall events in the 2000-2001 rainfall record was determined as 6 hours (Chapter 6) and therefore assuming a constant discharge therefore misrepresents rainfall/runoff and sediment transfer in upland catchments. Historical sediment loads are calculated from discharge based on contemporary sediment rating curves and the amount of over or under-estimation of contemporary sediment loads is dependent on the form of the sediment-rating model. As revealed in Figure 6.6 the sediment rating curves from Burnhope and Langtae differ. A low b-coefficient (0.8758) in the Langtae model corresponds to small variations in suspended sediment concentration with discharge.

Table 7.1 Comparison between bias corrected sediment yields determined from contemporary monitoring and long-term daily rainfall totals.

	Sediment yield ($t\ yr^{-1}$)	Specific sediment yield ($t\ km^{-2} yr^{-1}$)	% Error compared to contemporary measurements
Historical (1936-98) *			
Burnhope general	229.5	19.4	17% underestimation
Burnhope seasonal	157.2	13.3	33% underestimation
Langtae	173.5	57.8	401% overestimation
Contemporary (2000-01)			
Burnhope general	275.2	23.4	
Burnhope seasonal	233.2	19.8	
Langtae	43.2	14.4	

* Mean sediment yield

The high b-coefficient (1.15969) in the Burnhope regression model reflects larger changes in suspended sediment concentration with discharge. These variations in sediment transfer relationships between adjacent catchments result in very marked differences when estimating historical suspended sediment loads from historical daily rainfall totals.

Table 7.2A and B are worked examples showing the effects of assuming constant runoff rates when estimating sediment loads from historical rainfall daily totals. Figure 7.20A and B are plots of the variation in sediment load estimates when daily runoff of 25 000 m^3 is averaged over 24, 12, 6, 3 and 1.5 hours for the Langtae and Burnhope systems respectively. The Langtae model (Figure 7.20A) shows a positive trend with increasing sediment load estimation with runoff duration. The Burnhope model (Figure 7.20B) shows an alternative negative trend with a decrease in suspended sediment load estimation as runoff is averaged over longer timescales. The Langtae model has a more consistent trend in comparison to the Burnhope model, which shows little variation in load estimation when runoff is averaged between 6 and 24-hours. These models can be compared to the form of the general regression models of Burnhope and Langtae (Figure 7.20C). When runoff is averaged over 24-hours in the Langtae system, the gently sloping rating-curve results in the highest estimates of sediment load. This consistent average runoff is un-representative of the nature of upland systems and high magnitude, low frequency events are most common with higher runoff over shorter durations. When runoff over shorter durations is considered in the Langtae system, the small variations in suspended sediment concentrations with discharge reflected by low b-coefficients result in smaller sediment loads (Figure 7.20A). As suspended sediment loads calculated from historical daily rainfall in the Langtae system are based on runoff averaged over 24-hours, historical loads over-estimate contemporary loads that are based on real-time discharge readings.

The steeply sloping rating curve of the Burnhope system (Figure 7.20C) and subsequent large variations in suspended sediment concentration with discharge result in low concentrations at low discharges. When runoff is averaged over 24-hours this equates to lower discharge (cumecs) and suspended sediment concentrations, which provide underestimated historical sediment loads in comparison to contemporary loads. The form of the relationship between sediment load estimation and runoff for the Burnhope system (Figure 7.20B) shows little variation in sediment load estimation when runoff is averaged over 6 to 24-hours. The form of this relationship provides a more robust model for estimating sediment yield from historical rainfall totals.

Table 7.2 Calculation of suspended sediment load based on daily runoff averaged over varying storm durations in the (A) Langtae and (B) Burnhope systems.

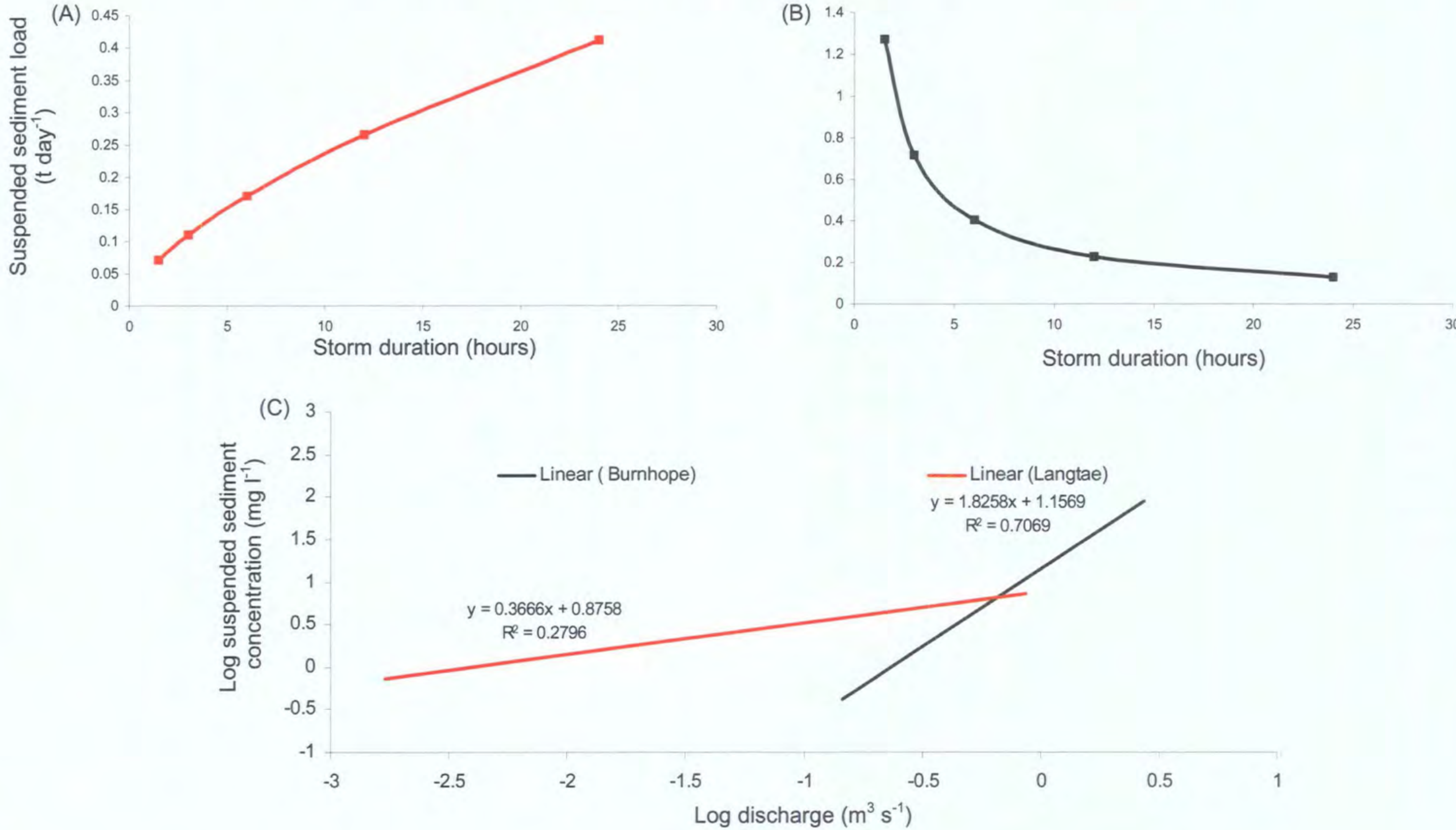
(A)

Daily runoff (m^3)	Storm duration (hrs)	Runoff ($m^3 s^{-1}$)	Load (t day^{-1})
25000	24	0.289	0.412
25000	12	0.579	0.266
25000	6	1.157	0.171
25000	3	2.315	0.110
25000	1.5	4.630	0.071

(B)

Daily runoff (m^3)	Storm duration (hrs)	Runoff ($m^3 s^{-1}$)	Load (t day^{-1})
25000	24	0.473	0.316
25000	12	0.945	0.559
25000	6	1.890	0.991
25000	3	3.781	1.757
25000	1.5	7.562	3.115

Figure 7.20 Suspended sediment load estimates based on variations in the distribution of daily runoff in the (A) Langtae and (B) Burnhope systems. The forms of these relationships are compared to corresponding sediment rating models (C).



These findings have important implications when attempting to model suspended sediment loads in small upland catchments based on daily records. Further data are required on a sub-daily basis to provide a better understanding of the relationship between suspended sediment concentration, discharge and rainfall. This information could be used to develop correction factors that account for variations in sediment transfer regimes in different upland catchments when load estimations are based on daily rainfall records.

7.5.2 Estimates of long-term yields from reservoir sedimentation

Three methods have been used to estimate long-term yields from reservoir sedimentation (Figure 7.19). Attempts were made to use bathymetric surveying techniques, core depths and evidence from oblique photographs to determine the active area of sedimentation. The contours in Figure 7.21A were digitised from construction plans of the reservoir basin from 1935. A resurvey of the basin bathymetry was conducted in 2000 using a SonarLite portable single beam echo sounder system and a differential Global Positioning System (GPS) and the resulting plot is shown in Figure 7.21B. It was intended that overlaying the echo-sounding survey and the original basin bathymetry would provide estimates of long-term sediment yields for Burnhope Reservoir, but due to the resolution of the survey and low sedimentation this method was not successful. Despite the uncertainties with estimating sediment depths for volume calculations, these surveys are useful for comparing reservoir bed topography and identifying potential zones of sediment focussing. Comparison between the original contours and the bathymetric survey shows there was little difference between the 1936 and 2000 surveys. There is a minor infill of sediment at the head of the main basin highlighted in red in Figure 7.21B that is evident on Figure 7.9 at the left of core 9. This is the only area of sediment focussing evident.

7.5.2.1 Oblique air photographs

Air photographs taken at low reservoir levels during the drought years of 1989 and 1991 were used to assess the spatial distribution of sedimentation. Figure 7.22 is an annotated photograph taken of the reservoir in draw down during 1991 and inset A highlights the dry stonewalls that marked boundaries of valley-floor fields prior to impoundment. These walls are still visible and this denotes the levels of sedimentation on the marginal slopes of the reservoir since impoundment. Using this information

Figure 7.21. Bathymetry of Burnhope Reservoir (A) digitised from 1935 construction plans and (B) from 2000 echo-sounding survey.

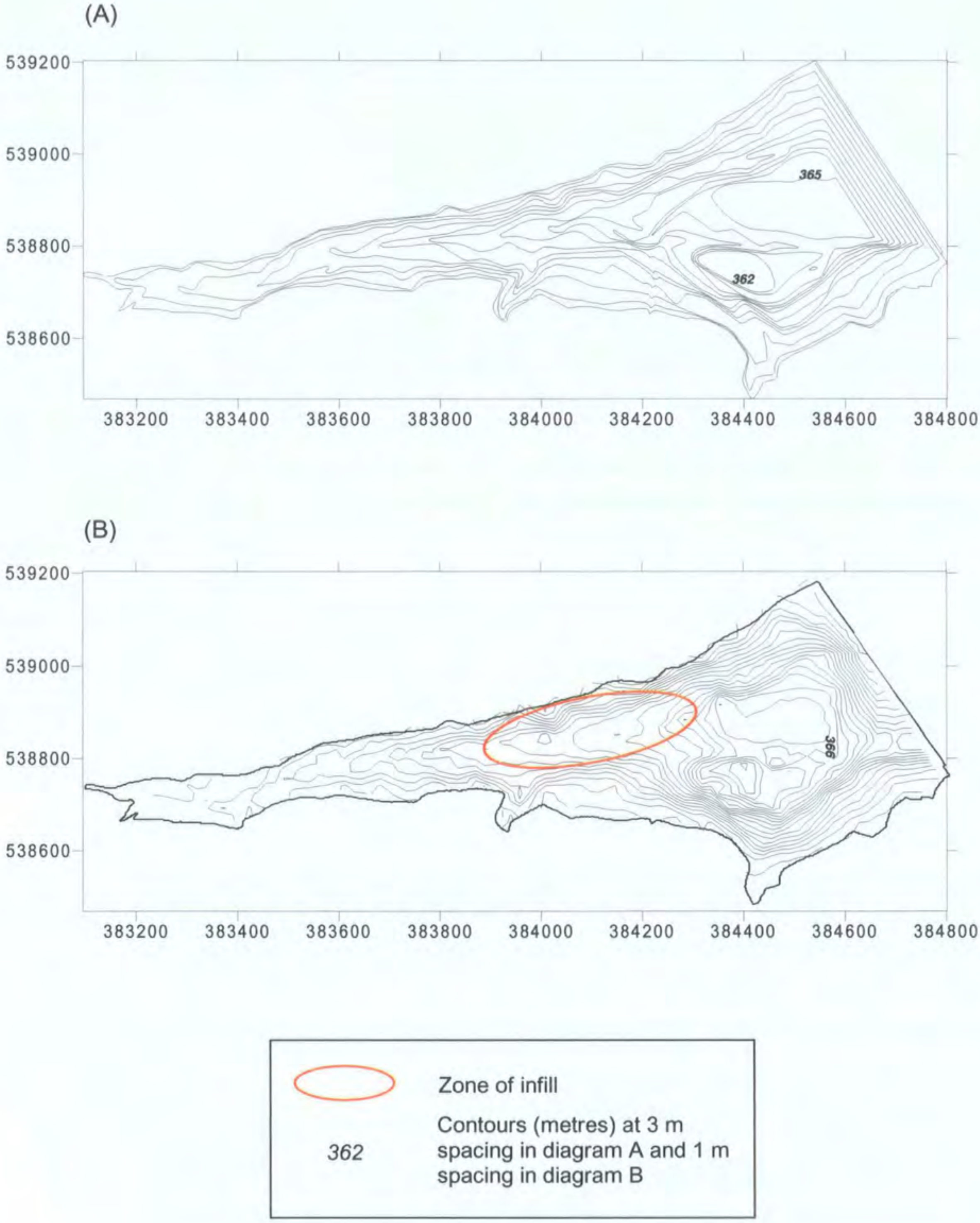
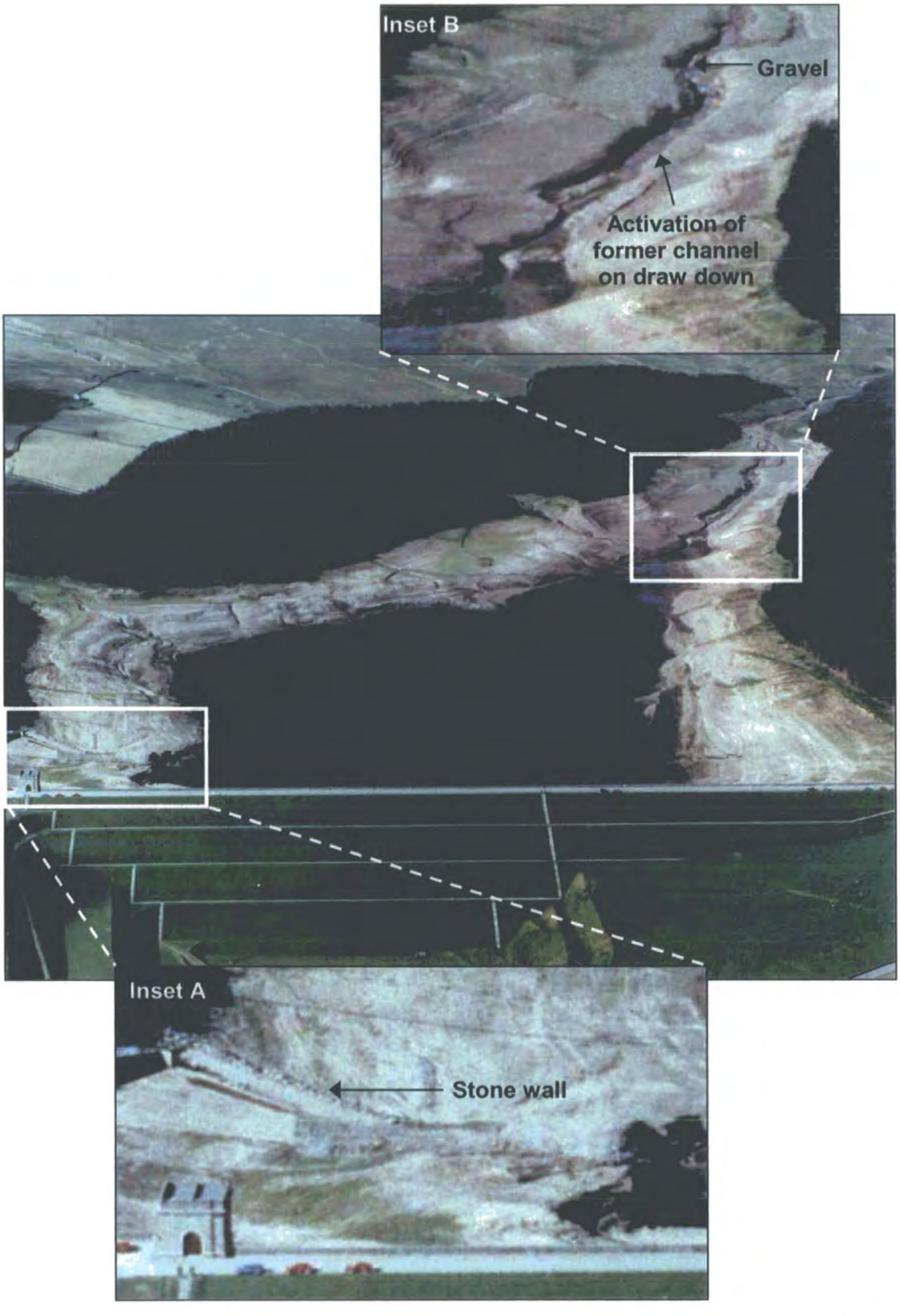


Figure 7.22 Photograph of Burnhope Reservoir during a period of down draw during drought conditions in 1991 used to establish the depth and area of sedimentation for calculating long-term sediment yields. Inset A shows exposure of a dry stonewall, a field boundary from pre-impoundment farms while inset B shows channel incision down to gravels and terraces of deposited sediment.

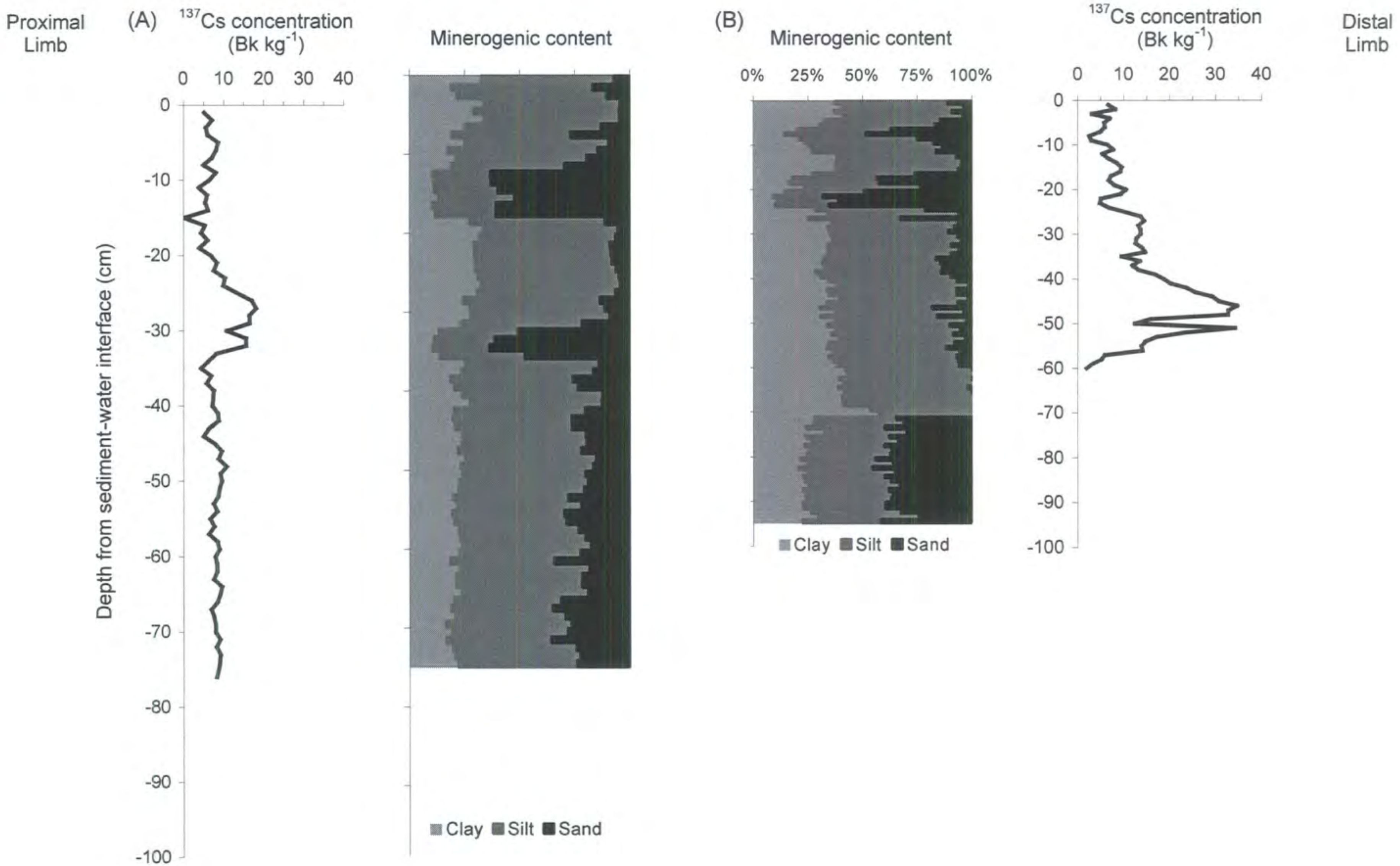


together with the reservoir bathymetry data, sediment deposition appears low around the periphery of the basin due to the steep gradient of the slopes and marginal reworking of sediment during fluctuations in reservoir levels. Inset B of Figure 7.22 shows that the majority of the pre-impoundment channel is exposed down to a gravel base at the proximal end of the basin. Small terraces formed as the channel incised into the channel fill sediments. These terrace heights indicate that sediment deposition along the course of the pre-impoundment channel is relatively low and decreases with distance upstream.

Reservoir core records were used to calculate the average depth of sediment accumulation in the reservoir. Figure 7.23 is a diagram of the minerogenic content of cores 1 and 8. Dating of the cores using ^{137}Cs has enabled the minerogenic content of these cores to be correlated and provides information on the average depth of sediment accumulation at different locations in the reservoir. Core 8 is used as the reference core as the lining of the reservoir is clearly apparent at approximately 70 cm (Figure 7.4 and 7.23) and this core was taken from a central location in the reservoir. The remaining cores did not record the same abrupt change in minerogenic content, but based on the geometry of the sedimentary basin, it is assumed that sediment depth would unlikely exceed one metre. Average dry bulk densities of the core sediments were used together with core depths to estimate the mass of sediment at each reservoir core location.

Each of the three methods used to estimate sedimentation in the reservoir provides valuable information for understanding the temporal and spatial distribution of sediment in the reservoir basin. The bathymetry provides information comparing reservoir bed topography from impoundment to the present day, while air photographs are used to assess the spatial distribution of sedimentation. Together these information sources have been used to denote low sediment deposition on the marginal slopes of the reservoir and relatively low sedimentation along the proximal limb of the reservoir. These methods provide sedimentation information over the whole basin in areas of the reservoir not suitable for core sampling. Individually, results from bathymetric surveying and information from air photographs could not be used in study to provide reliable data on sediment accumulation. However, combining the techniques has proved valuable in determining the active area of sedimentation. Sampling of reservoir sediments and determining core chronology provides high-resolution, reliable data on average depth of accumulation at specific locations along a core transect. Variations in sedimentation at different locations in the reservoir can be investigated using core chronology but without an idea of sediment distribution over the whole basin, reliable

Figure 7.23 Core correlation diagram showing minerogenic content of (A) core 1 and (B) core 8 both dated using ^{137}Cs.



estimates can only be made at specific locations. The information from high-resolution core data together with low-resolution data on sedimentation distribution across the whole reservoir basin enables the active area of sedimentation within Burnhope Reservoir to be estimated with relative accuracy.

The 'average contour area method' was considered for estimating sediment depths at different contour altitudes but because of the irregular spatial distribution of cores and the steep side slope gradient of bed contours this was not an appropriate technique. As an alternative, the reservoir area was split into geometric prisms and the volume of sediment in each determined from bulk density and depth of individual cores and the area of the prism. These sections were summed to calculate the total volume of sediment within the active sedimentation zone. Table 7.3 shows the results of total sediment volume and mass split into the minerogenic and organic fractions. The organic content of the sediments was based on the mean loss on ignition value from core sediments of 15.3% by weight.

Table 7.3 Organic and minerogenic sediment yields (based on loss on ignition values) calculated from reservoir sedimentation estimates.

	Total	Minerogenic (84.7% by weight)	Organic (15.3% by weight)
Reservoir sediment volume (m^3)	63165	53500	9664
Mass of sediment since impoundment (t)	37899	32100	5798
Estimated annual sediment accumulation (t)	592	501	91
Catchment specific sediment yield (t km^{-2} yr^{-1}) *	33.3	28.2	5.1

* Based on direct catchwater area of 17.8 km^2

7.6 Chapter summary

Analysis of core sediments has provided information on the spatial distribution and temporal accumulation of sediment in Burnhope Reservoir. A general fining of sediment towards the dam has been observed due to sediment focussing in the deeper parts of the reservoir. The trends in ^{137}Cs concentration in core sediments from the proximal and distal sections of the reservoir conform to the classic shape of atmospheric fallout, although comparison between cores reveal particle enrichment of ^{137}Cs in the distal section. The ^{137}Cs profile has enabled sedimentation rates of 0.77 and 1.24 cm yr^{-1} to be determined in dated cores from the proximal and distal sections of the reservoir respectively. The presence of coarse-grained layers in cores 1 and 8 have been dated as post 1976 and these relate to diverging trends in winter and summer-centred rainfall totals identified through analysis of long-term daily rainfall records. The magnitude, frequency and timing of reservoir water level fluctuation related to these diverging trends in seasonal rainfall has been identified as a key variable in assessing sediment transfer, deposition and reworking in the reservoir.

The onset of deposition of the coarse-grained layers has been interpreted in two ways. First, analysis of oblique air photographs has revealed activation of the pre-impoundment channel in the proximal limb of the reservoir during periods of draw down, providing potential sources of coarse-grained sediment to the distal section of the reservoir. The second interpretation has been related to variations in catchment sediment transfer in response to the record of diverging seasonal rainfall totals. Without further investigation into sediment provenance, and the dynamics of sediment routing through the reservoir the exact source of these sediments cannot be determined.

Sediment yields have been estimated using three approaches, the first from contemporary monitoring (Chapter 5), the second from historical rainfall records and the third by estimating the active area of sedimentation using air photographs, bathymetry and core records and using calibrated core depths to calculate sediment volumes. Each of these three methods used have provided valuable information for understanding the temporal and spatial distribution of sediment in the reservoir basin. The information from high-resolution accumulation data from reservoir cores together with low-resolution data on sedimentation distribution across the whole reservoir basin using bathymetry and air photographs has enabled the active area of sedimentation within Burnhope Reservoir to be estimated with relative accuracy. Annual sediment accumulation in the active area of sedimentation has been estimated at 592 t of which

84.7% (501 t) is minerogenic sediment. This equates to a specific yield of 33.3 t km^{-2} year. Estimates from historical rainfall records and contemporary monitoring have provided slight underestimates of sediment load for the Burnhope catchment, with estimates from historical rainfall records underestimating contemporary yields between 17-33% for general and seasonal rating models respectively. The yields calculated from historical daily rainfall data produced 401% overestimates of yields from contemporary monitoring. The discrepancies between historical and contemporary sediment load estimations have been attributed to calculations of historical daily sediment loads from runoff (cumecs) averaged over the 24-hour period. Assuming consistent runoff is unrepresentative of natural stream-flow in upland systems. The amount that historical sediment loads under or over-estimate contemporary sediment loads is dependent on the form of the sediment rating relationships for individual catchment systems.

CHAPTER 8 - SUSPENDED SEDIMENT BUDGET FOR BURNHOPE RESERVOIR

8.1 Introduction

The aims of this chapter include combining sediment yield estimates from stream monitoring with those calculated from reservoir sedimentation and reservoir shoreline monitoring to develop a reservoir sediment budget and evaluate sediment delivery from the catchment to the reservoir. The chapter consists of four sections. The first uses sediment yield data from contemporary stream monitoring and reservoir sedimentation to construct an annual sediment budget for Burnhope Reservoir. Error terms are calculated for measured components and the rationale behind reporting errors in sediment budget studies outlined. Comparisons are made between previous published studies of sediment yield estimates from upland catchments and those from Burnhope Reservoir and river monitoring in the Burnhope and Langtae catchments.

The second section examines the interrelationships between the characteristics of the Burnhope and Langtae catchments (Chapter 2), catchment sediment sources and sediment dynamics (Chapters 4 and 5). This enables the spatial and temporal scales of sediment transfer in the Burnhope and Langtae catchments to be investigated.

The third part investigates the reservoir sediment storage component of the budget. Physical and radiometric analysis of reservoir sediments provide evidence of long-term changes in catchment sediment supply in relation to climatic fluctuations and variations in reservoir water level.

Finally the impact of contemporary climate and the role that recent climatic change has had on sediment transfer to Burnhope Reservoir is considered. Discussion is extended to include the impacts of future climatic change on upland sediment systems in the UK.

8.2 Sediment budget for Burnhope Reservoir

Sediment budgets provide a conceptual and quantitative model of sediment transfer and pathways for a given time period (Rosati and Kraus, 1999). The complexity of landscape units present problems in quantifying all the components of these budgets and many terms remain unmeasured. These unmeasured terms are called residuals and have been determined by subtraction in a number of published sediment budget studies. A number of these studies are summarised by Kondolf and Matthews (1991). Both measured and residual components contain error, but few studies have reported the uncertainties in budget components. Error calculations on these components are essential for quantifying measurement errors of best estimates. Figure 8.1 is a suspended sediment budget for Burnhope Reservoir for the 2000-2001 study period. It highlights both the measured and residual components and also provides error terms for the main components of the system. Figure 8.2 is an error tree showing the error terms of each sediment budget component revealing how errors from individual components propagate through to balance the sediment budget. Further discussion on calculation of errors in budget components is included in Section 8.2.2.

The reservoir outputs in Figure 8.1 include outflows to the treatment plant for domestic use, piped water to Waskerley Reservoir and compensation outflows to Burnhope Burn downstream of the dam. Northumbrian Water Limited (NWL) provided estimates of suspended sediment loads from these outflows based on average turbidity readings recorded during 2000 and 2001. These turbidity readings (NTU) have been converted to total suspended solids (mg l^{-1}) on the basis of suspended solids determinations from raw water samples from the reservoir outflow. Inputs to the reservoir are both allothochonous and autochthonous. Atmospheric dust fallout, shoreline bank erosion and suspended sediment loads from the drainage basin are all allothochonous inputs. No figures were available for local atmospheric dust inputs for Burnhope; however, dust fallout over rural areas the UK has been estimated at between 0.02 and 0.2 kg km^{-2} yr^{-1} (Simmons, 1974). Even the upper range of this estimate for dustfall is almost negligible and the component has been considered negligible in the Burnhope sediment budget.

Shoreline erosion has been estimated from preliminary monitoring of reservoir banks from November 2000 to January 2001. The extent of exposed and actively eroding banks around the reservoir was determined from field mapping and ten monitoring sites were established for bank erosion measurements using erosion pins. The average height of

Figure 8.1 Annual fine sediment budget for Burnhope Reservoir. Inflows, outflows and storages (boxes) based on data from 2000 and 2001. Arrows are proportional to fluxes.

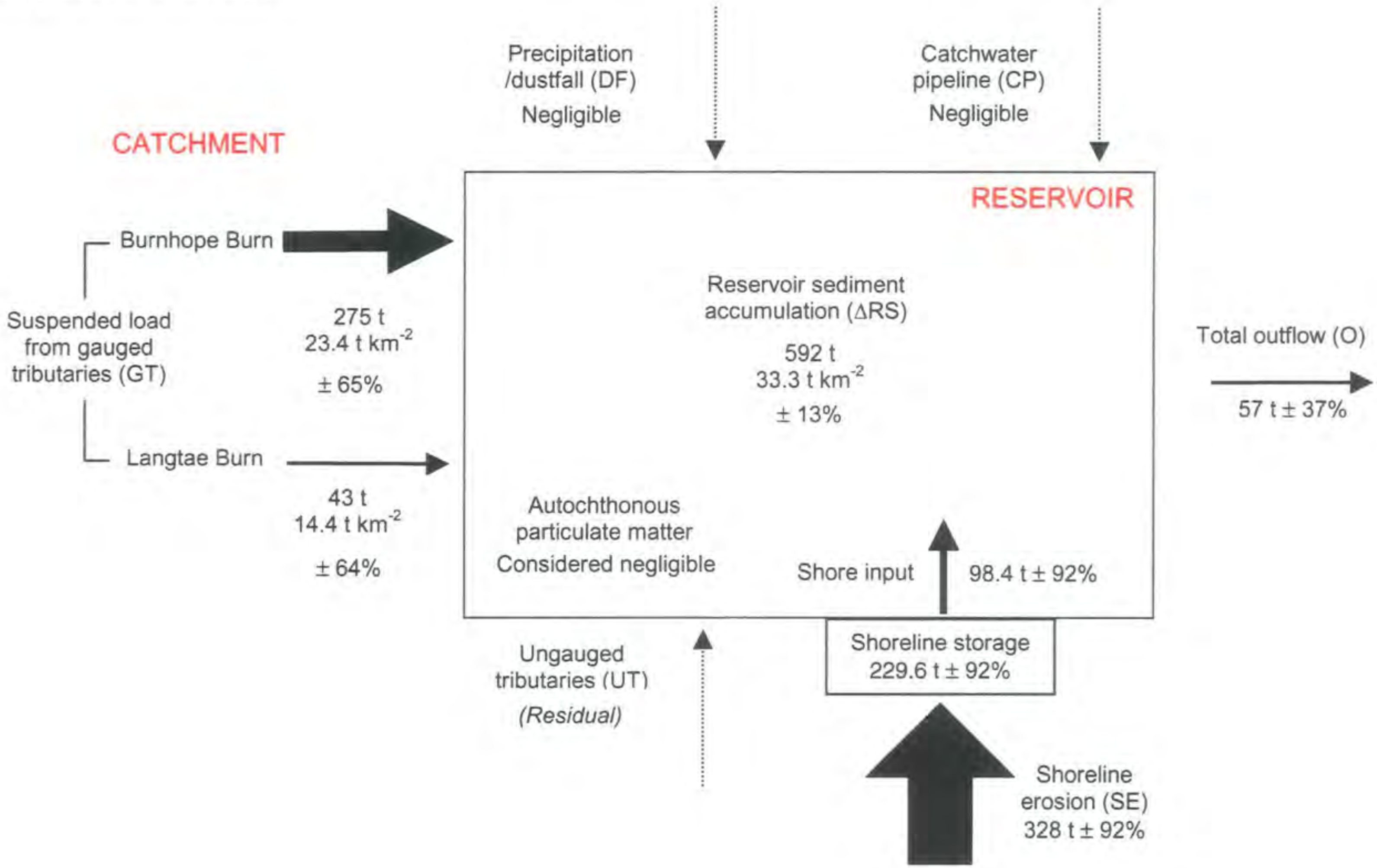
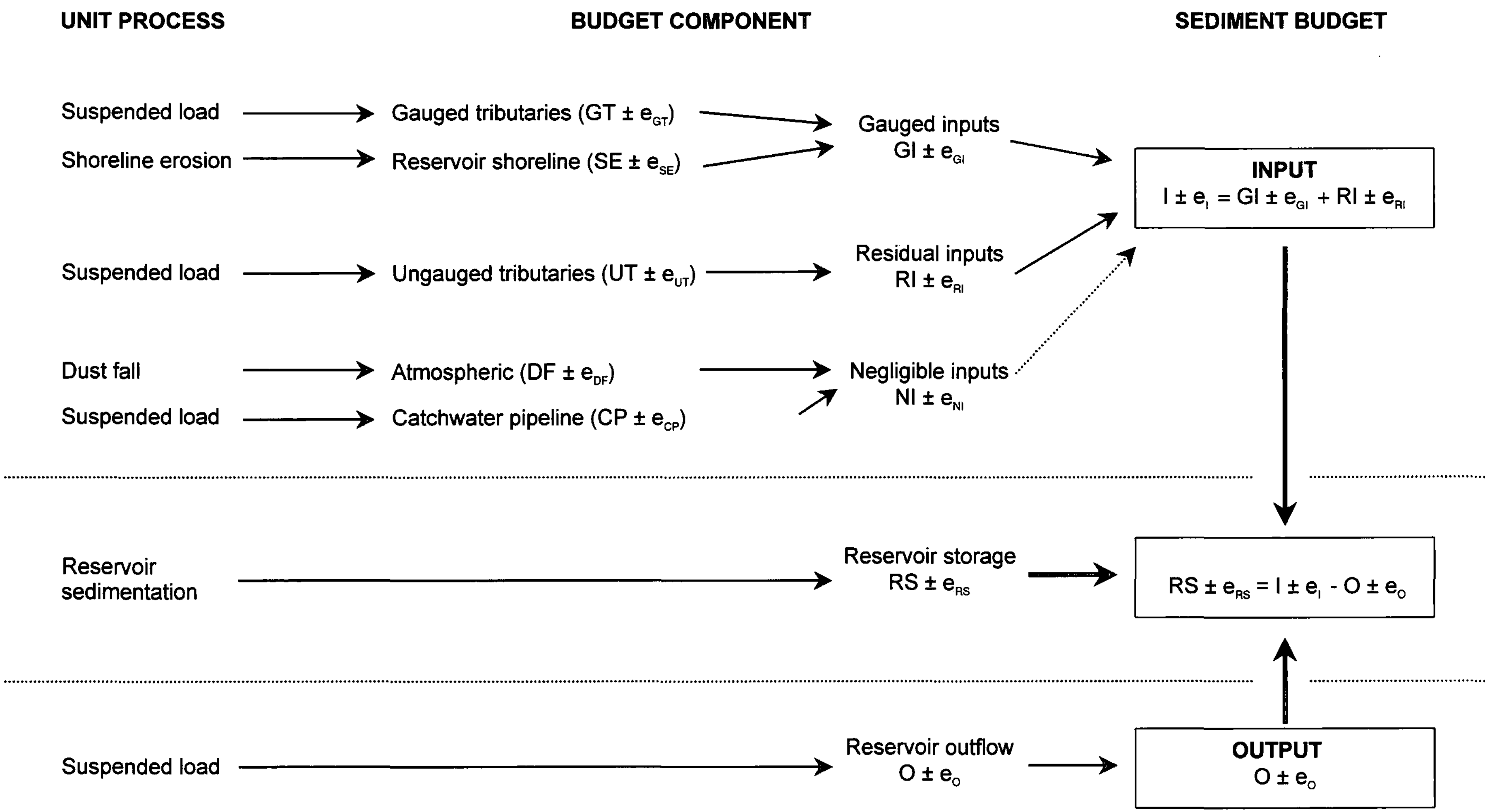


Figure 8.2 Error tree showing the error terms of each sediment budget component.



eroding banks is 1.58 m. The total length of eroding banks is 1353 m, which equates to 44% of reservoir shoreline. These banks were recorded as eroding at an average rate of 34 mm over the two-month period from December 2000 to January 2001. If an annual erosion rate was calculated based on this two-monthly rate it would be an overestimate as it accounts for erosion during the winter months when processes of freeze thaw and needle ice development are prevalent.

The influence of frost action on bank erosion has been studied in detail in the Upper Severn basin (Lawler, 1987; Lawler *et al.*, 1997; Bull, 1996; Stott, 1998). Research revealed that the majority of material removal took place during the winter months (December to March) when bank surfaces were subject to freeze-thaw processes. Bull (1996) revealed monthly bank sediment yields for January 1995 from sites in the Caersws catchment as an order of magnitude greater than those recorded during the summer months. Stott (1998) reported 89% of annual bank erosion in Afon Tanllwyth occurring during the winter months. Research into mean bank erosion for three-monthly periods in the Monachyle and Kirkton catchments in the Southern Highlands of Scotland revealed that approximately 50% of bank erosion occurred during the winter months (January to March) (Stott, 1997). Less than 12% of erosion occurred during the summer (July to September) and 20-25% of the annual erosion took place during the spring (April to June) and autumn months (October to December) (Stott, 1997). Stott (1997) reports mean annual bank erosion rates of 59 and 47 mm yr^{-1} for the Monachyle and Kirkton catchments respectively. These rates are comparable to those recorded from the shoreline of Burnhope Reservoir, which has erosion rates of 34 mm recorded for the two-month period (December to January). Due to the truncated monitoring period of shoreline erosion at Burnhope, the budget input estimates from this component have been corrected in line with findings of Stott (1997). If winter erosion rates and yields account for 50% of the annual total, the average volume of sediment eroded from exposed banks is estimated at 72.7 m^3 for this two-month period, equating to 328 t yr^{-1}± 92% using soil-packing densities for silt/gravel matrices of 1.8 g cm^{-3} (Selby, 1982).

The high percentage error on yield estimates from banks along the Burnhope Reservoir shoreline highlights the range of variation between rates of loss at different sites. Field observation provides evidence of needle ice formation on north facing banks and sporadic bank failures during the winter months that are considerable point sediment sources to the budget and could account for the large variations in erosion rates between sites. From field observation it is apparent that the majority of eroded sediment from shoreline erosion is held in local sediment storage at the slope toe. Figure 8.3 shows evidence of coarse and fine-grained sediment storage on a north-facing bank of the reservoir shoreline. Particle size analysis of eroded sediments sampled from the shoreline of Catcleugh Reservoir in Northumberland (impounded on similar geology to Burnhope Reservoir) revealed that 70% of the sediments had grain sizes > 2 mm and this fraction remained in storage at the toe slope (Warburton, 2003). From observation at Burnhope Reservoir (Figure 8.3) it is assumed that 70% of the sediment eroded from the shoreline has grain-sizes > 2 mm, which remains in storage at the reservoir margins. The remaining 30% of sediments in the finer particle-size fraction (< 2 mm) is reworked by runoff and wave action during the winter months when the reservoir is at full capacity, and settles into deep-water storage.

Suspended sediment inputs from the catchments of Burnhope and Langtae have been estimated from monitoring (Chapter 5). Although these catchments are the largest feeding Burnhope Reservoir there are 3 km^2 of drainage basin containing streams that directly feed the reservoir, which remained un-gauged. This un-gauged area is similar in size to the Langtae catchment, but consists of three smaller channel networks with combined drainage densities greater then that recorded in the Langtae catchment. The inputs from these un-gauged tributaries form the unknown residual of the reservoir sediment budget (Figure 8.1) and can be determined from subtraction. Further discussion on calculation of the residual component and the error associated with it is included in Section 8.2.3.

Within the reservoir, sediment accumulation was calculated assuming average annual sedimentation rates of 0.77 and 1.24 cm yr^{-1} based on ^{137}Cs core chronologies from cores 1 and 8 respectively. Any autochthonous inputs from aquatic productivity or biogenic precipitation are included in these sedimentation rates but no estimates are available for these autochthonous contributions. Few studies account for autochthonous inputs in reservoir sediment yield studies. Estimates of diatom silica contributions to the minerogenic sediment fraction in the Merevale catchment in Warwickshire were quoted as 2-3% in old and 4-6% in new sediments (1-10 cm of the core) (Foster *et al.*, 1985). For sediment yield estimates from the Southern Pennine reservoirs, no correction for autochthonous inputs is justified on the basis that organic productivity is restricted in acidic stream waters (Labadz, 1988). Trap efficiency estimates for Burnhope Reservoir are shown in Table 8.1. Estimates are based on Brune's (1953) trap efficiency curves and on the sediment balance equation from the reservoir sediment budget. The ratio of inflow to capacity of 0.2 equates to a trap efficiency of 92% based on Brune's (1953) curves.

Figure 8.3 Photograph of north facing bank of Burnhope Reservoir shoreline showing coarse and fine eroded bank material in local toe slope storage.

Table 8.1 Trap efficiency calculations.

Mean recorded annual inflow 1991-1994 (Ml)	34356
Capacity of the reservoir (Ml)	6440
Capacity:inflow ratio	0.2
Envelope range (%)	87-97
Brune's trap efficiency (%)	92
Sediment budget derived estimate (%)	96

A greater estimate of 96% was calculated using the sediment balance equation, which still corresponds to the estimate from Brune's (1953) model as the value lies in the envelope range of 87-97%. Based on these trap efficiency estimates it appears trap efficiency was slightly underestimated using Brune's (1953) curves.

The proportional arrows in Figure 8.1 highlight the major components of the budget revealing shoreline bank erosion as the highest contributor. However, based on the seasonality of bank erosion processes described above, the yields estimated from this component may greatly bias the sediment budget due to the truncated monitoring period. Based on field observations, the storage component of sediment from shoreline erosion accounts for 70% of this major component and on the basis of uncertainty in shoreline measurements and storage, the contributions of fine sediments to the reservoir budget from shoreline erosion are secondary to those influxes from gauged tributaries (Burnhope and Langtae Burns). The best estimate of inputs from the monitored direct catchwaters total 318 t yr^{-1} ± 129 which is 54% of the total sediment estimated to accumulate in the reservoir per year.

8.2.1 Potential errors in sediment budget research

Without detailed error analysis, comparison between different sediment budget studies is difficult (Harbor and Warburton, 1993). Error specification is especially important when calculating residuals via the subtraction method. Kondolf and Matthews (1991) published a cautionary note stressing that unmeasured residual terms incorporate not only the sediment budget components attributed to them, but also the net sum of the errors in measured components. It is for this reason that all significant errors should be reported and also that residual terms calculated via the subtraction method should be identified as such.

Rosati and Kraus (1999) claim that uncertainty consists of *error* and *true uncertainty*. The errors can be either random or systematic, those that can be revealed by repeating an experiment are considered random while those that can not be revealed by repetition are systematic (Taylor, 1997). The most common source of error is in measurement, both human and instrument based. Human error, such as the reading of a meter is considered random, whilst readings from an incorrectly calibrated instrument will produce systematic errors if recalibration is not an option. Random errors can be accounted for using statistical techniques such as standard deviations or standard error of measurements of regression coefficients, while systematic ones are usually hard to identify and evaluate (Taylor, 1997). True uncertainty may not be linked to the measurement process, but be due to natural variability (e.g. temporal and spatial extrapolation) and is inherent in all physical measurements.

8.2.2 Field measurements and sources of error

Basin sediment yield was estimated from measurements of suspended sediment transport from the direct catchwater input streams, Burnhope and Langtae Burn. Suspended sediment was collected by an automatic sampler as opposed to manual sampling to reduce random error. Water samples were vacuum filtered in the laboratory though filter papers that were weighed before and after drying. The balances have an error margin of ± 3%. Discharge was determined using a velocity meter with a standard error margin of ± 0.5%. Measurement errors of water depth and cross sectional area must be included here as discharge was calculated using the velocity area method. In order to determine unknown suspended sediment concentrations from known discharge values, extrapolation techniques were used and the resulting regression equation applied in the prediction of suspended sediment concentrations for known discharge values. The error inherent in the basin sediment yield estimates, are principally related to the prediction of suspended sediment concentrations using the regression equation.

The sources of the errors inherent in the shoreline inputs are three-fold. Measuring erosion pins using calipers attracts a degree of human and instrumental random error. Issues of averaging erosion rates and bank heights from different sites can lead to both over- and under-estimation of sediment volumes. Thirdly, the most prominent source of error in the shoreline erosion component is related to the timing of the monitoring period, both seasonally and temporally. The truncation of the field season due to foot and mouth disease resulted in shoreline measurements from December to January only. This error is difficult to quantify on the basis of the limited data set.

The errors in the reservoir storage calculation are laboratory based and random in nature. Sub-sampling of the core into 1 cm sections incurred an error of approximately ± 10%. This error cancels due to continuous sampling down core. Bulk density measurements on these 1 cm sub-sampled core sediments using a modified volumetric syringe incurred errors of approximately 10% due to the inability of the syringe to remove 100% of sediment from the petri dish. Errors from the balance should once again be included here, and together, these errors propagate through the conversion of sediment volume to mass. No doubt the largest error inherent in determining reservoir sediment storage is in the use of volumetric prisms to estimate sediment volumes from the reservoir. Average sediment depths from core records were extrapolated on the basis of bathymetric data and draw-down photographs to determine the area and depth of the accumulated sediment. It is not possible to fully quantify the errors involved in this method.

A summary of the main types of error in this budget include:

1. Error associated with predictions from regression relationships (suspended sediment yield estimates).
2. Laboratory error in determining the volume and mass of sediment.
3. Random errors involved in field measurements using measuring equipment (calipers, tape measures).
4. Errors of spatial extrapolation.

The first three sources of error in the above list are random in nature and can be accounted for using statistical techniques including standard deviations and standard error. The fourth source is more difficult to quantify. An example of a method to determine error for calculations of sediment yields from reservoir sedimentation is provided by Evans (1997) who used an innovative approach of error analysis of lake sediment derived yield estimates involving spatial extrapolation for Cathedral Lake basins in British Columbia. This method is only applicable in studies where a grid coring system has been used and unfortunately this system of core retrieval was unable to be used at Burnhope due to slope gradient of the reservoir basin.

8.2.3 Balancing the sediment budget

Now the errors have been highlighted for each of the principal components of the sediment budget it is possible to quantify sediment yield estimates of individual budget components with their associated errors and calculate the residual budget component via subtraction. The outcome of the budget is encouraging in the respect that the major components of the system have been identified and quantified. Table 8.2 is a summary of the fine sediment fluxes of sediment budget components and their maximum error values. Using the subtraction method to determine sediment yields from un-gauged tributaries provides an estimate of 232.6 t. The error associated with this component is summative and calculated from maximum measured error in all measured budget components. The specific estimate of annual sediment yield from un-gauged tributaries can be considered high in relation to the sediment yield determined from monitoring of Langtae Burn even when the higher drainage density in the un-gauged catchments is considered. However, the large error term related to the residual component highlights the uncertainty inherent in this estimation.

Development of this sediment budget for Burnhope Reservoir has highlighted the importance of shoreline erosion as a potential sediment source to the reservoir system and has also revealed the importance of shoreline storage of sediment eroded from reservoir banks. Identifying these potential sediment sources and stores and quantifying potential sediment supply via these components is crucial when estimates of long-term catchment erosion are determined from reservoir sedimentation. Inputs of sediment from eroding reservoir banks could be considered as accounting for 55% of the total inputs to the sediment budget. However, with identification of the shoreline storage component and selective particle-size fractions, the input of fine sediment to the budget is reduced to 17%. The majority of suspended sediment yields calculated from reservoir sedimentation in other published studies are either expressed as an individual catchment statistic or in conjunction with yields from river monitoring. There are few examples of published suspended sediment yield estimates expressed in a sediment budget framework that have considered shoreline erosion and storage as a major budget component (cf. Foster *et al.*, 1985).

8.3 Comparison of reservoir and catchment derived sediment yields with those from other upland catchments

Suspended sediment yield information is available for many areas of the world with values ranging from less than 2 t km^{-2} yr^{-1} to greater than 10,000 t km^{-2} yr^{-1} (Walling, 1994) with a global average of 190 t km^{-2} yr^{-1} (Mahmood, 1987). Sediment yields from British rivers are known to be low by global standards (DETR, 2001) and there is considerable spatial

Table 8.2 Summary of fine sediment fluxes of sediment budget components and their maximum error values.

Sediment budget component		**Sediment supply (tonnes)**	**Maximum measured error (tonnes)**
Storage	Reservoir storage (ΔRS)	592	77.0
Inputs	Gauged tributaries (GT)	318	206.3
	Shoreline erosion (SE)	98.4	90.5
	Ungauged tributaries (UT)	*Unmeasured residual* *	
	Dust fall (DF)	Negligible	-
	Catchwater pipeline (CP)	Negligible	-
Total measured inputs (I)		416.4	296.8
Outputs	Reservoir outflow (O)	57	21.1
Sediment balance			
O + ΔRS		649	91
I		416.4	296.8
* UT = O + ΔRS - I		232.6	394.9

variability in suspended sediment yields with annual totals ranging between 1 and 488 t km^{-2} yr^{-1} (Walling, 1987). There are also considerable temporal variations in sediment yields from individual rivers systems. Suspended sediment concentrations in British rivers have been recorded to vary up to three magnitudes within a year (DOE, 1995), while year to year variations in suspended sediment yield for one river (the Trent) have been recorded as varying as much as 590% (Wass and Leeks, 1999). Sediment yield estimates for upland catchments are rarely reported (Table 8.3).

Reservoir surveys and lake/reservoir bottom sediments have been used to provide longer-term information on catchment suspended sediment yields providing mean annual totals that average out the fluctuations in catchment sediment yields from short-term river monitoring (Chapter 7). Core chronologies have been determined using annual laminations in lake sediments (Curr, 1995) and also radionuclides of ^{137}Cs and ^{210}Pb in lake and reservoir sediments (van de Post *et al.*, 1997; Foster and Lees, 1999b). These dated cores have enabled variations in sediment yield to be determined and these fluctuations linked to environmental change such as land use practices (cf. Bonnett and Appleby, 1991; Bonnett and Cambray, 1991; van der Post, 1997) and climate (Wilby *et al.*, 1997; Foster and Lees, 1999a & b). Sediment yields estimated from reservoir sedimentation in upland catchments are listed in Table 8.4.

Figure 8.4 compares annual sediment loads with catchment area for published reservoir sedimentation and monitoring projects in upland regions of the UK using data from Tables 8.3 and 8.4. In Figure 8.4A the data are sub-sectioned into different land use types while Figure 8.4B analyses the relationship between catchment area and sediment load predictions using reservoir sedimentation and stream monitoring approaches. These sediment loads are all from small upland catchments less than 100 km^2. Comparison of estimated sediment yields based on both reservoir sedimentation and river monitoring is problematic owing to the assumptions made about reservoir trap efficiency, relative proportion of atmospheric autochthonous and allochthonous sediment accumulation and the different timescales and errors associated with the two methods. Despite these discrepancies, mean sediment yield estimates from published studies from reservoir sedimentation (Table 8.4) and stream monitoring (Table 8.3) are comparable, recorded as 53.7 and 59.2 t km^{-2} yr^{-1} respectively. Direct comparison between individual studies is complex due to the variations in spatial and temporal scales of sediment supply and the varying methodologies used to determine sediment yields (cf. Dearing and Foster, 1993).

Table 8.3 Sediment yields from stream monitoring in upland regions of the UK.

Site	Region	Dominant land use	Altitude (m)	Catchment area (km^2)	Sediment yields ($t\ km^{-2}\ yr^{-1}$)	Source
Monachyle	Balquidder	Moorland Ploughed	607	7.7	38.0 200	Stott *et al.* (1986)
Kirton	Balquidder	Forest 33% Clear-felled	623	6.9	54.0 361	Stott *et al.* (1986)
Upper Seven	Plynlimon	Moorland	610	0.94	66.2	Francis (1987)
Cyff	Plynlimon	Grassland	380-420	3.1	6.0	Moore & Newson (1986)
Tanllwyth	Plynlimon	Forest	360-380	0.9	38.0	Moore & Newson (1986)
Ceunant Ddu	Llanbrynmair	Moorland Ploughed	490	0.34	3.7 9.0	Francis & Taylor (1989)
Nant Ysguthan	Llanbrynmair	Moorland Ploughed	510	0.14	0.7 3.0	Francis & Taylor (1989)
Wessenden Head	South Pennines	Moorland	320-515	0.0042	55.0	Labadz (1988)
Coalburn	Carlisle	Moorland Ploughed Planted	515	1.5	3.0 25.0 13.0	Robinson & Blyth (1982)
Burnhope	North Pennines	Moorland	400-478	11.8	23.4	Current study
Langtae	North Pennines	Moorland	400-478	3.0	14.4	Current study
			Mean	3.3	53.7	

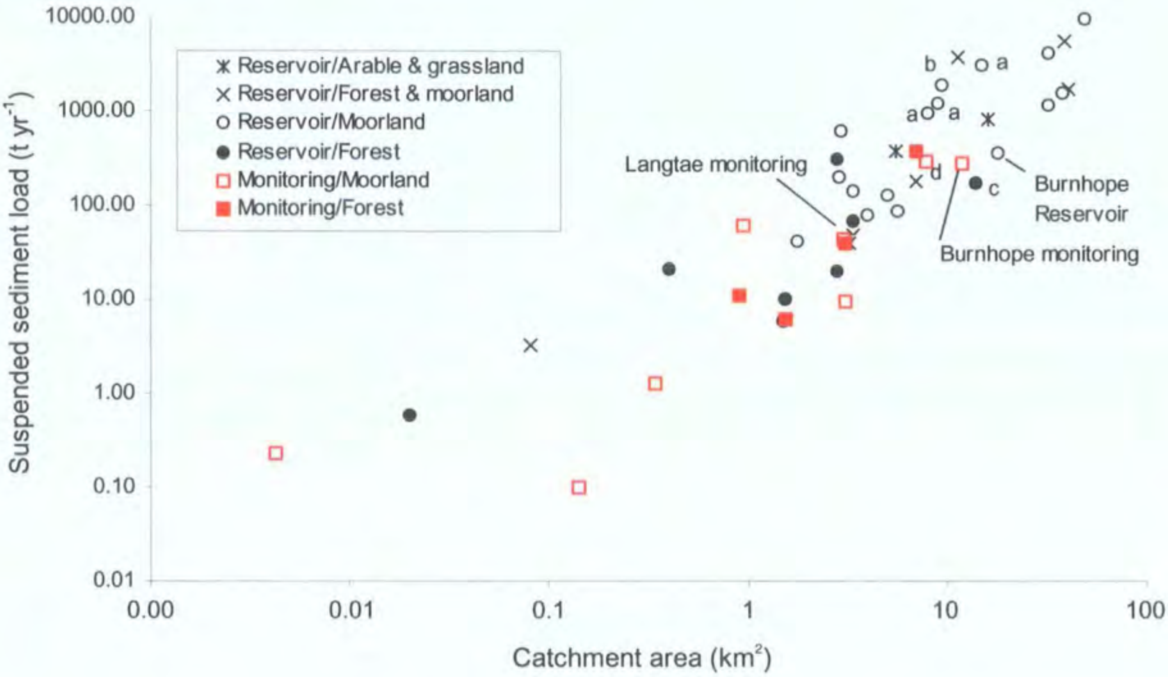
Table 8.4 Sediment yields from reservoir sedimentation studies in upland catchments of the UK.

Site	Region	Dominant land use	Altitude (m)	Catchment area (km^2)	Reservoir area (km^2)	Method	Percentage loss of capacity Total	Percentage loss of capacity Annual	Sediment yields (t km^{-2} yr^{-1})	Source
Barnes	Tweed catchment	Moorland	250-400	1.78	0.059	Coring	*	*	23.45	
Boltby	N.York Moors	Coniferous forest	220-336	3.4	0.022	Coring	*	*	16.48	
Elleron		Pasture	140-229	2.8	0.030	Coring	*	*	7.67	Foster & Lees (1999)
Fontburn	Tweed catchment	Coniferous forest	190-440	27.7	0.323	Coring	*	*	9.43	
Silsden	Aire catchment	Pasture	170-373	8.2	0.104	Coring	*	*	17.64	
March Ghyll	Yorkshire Dales	Moorland	210-380	4.0	0.057	Coring	*	*	34.60	
Pinmacher	Ayrshire	Forested	137-247	0.4	0.014	Survey	*	*	51.1	Duck & McManus (1994)
Harperleas		Moorland & forest	259-522	3.4	0.16	Survey & rodding	1.5	0.014	13.8	
Drumain		Moorland	231-318	1.5	0.02	Survey	1.4	0.012	3.9	
Glenquey		Moorland	287-643	5.6	0.17	Survey	1.1	0.01	15.1	
Holl	Midland Valley	Moorland & forest	204-440	4.0	0.18	Survey	4.6	0.054	72.3	Duck & McManus (1990)
Carron Valley		Moorland & forest	225-570	38.7	3.90	Survey	4.0	0.082	141.9	
Earlsburn		Moorland	367-460	2.9	0.26	Survey	8.7	0.089	68.2	
North Third		Moorland	171-441	9.3	0.46	Survey	14.3	0.186	205.4	
Catcleugh	Northumberland	Moorland & coniferous forest	250-550	40.0	1.4	Survey	*	*	43.1	Hall (1967), Walling & Webb (1981b)
Trentabank	S. Pennine uplands	Moorland	258-475	2.2	*	Survey	*	*	34.5-49.3	Stott (1985, 1987)
Howden	Peak District	Moorland	236-628	32.0	2.5	Survey Coring	*	*	35.7 127.7	Seven Trent Water Hutchinson (1995)
77 S. Pennine reservoirs	Lancashire	Moorland	-	1.2-114.9	-	Survey	Mean 10	Mean 0.11	Mean 124.5 Median 77.0	Labadz *et al.* (1995), White *et al.* (1996b)
Wessenden Valley chain (4 reservoirs)	Yorkshire	Moorland	-	-	-	Survey	*	*	Mean 203.7	Labadz *et al.* (1991)
Burnhope	N. Pennines	Moorland	400-478	17.8	0.8	Coring	0.6	0.009	33.3	Present study
		Mean		**12**			**5.1**	**0.063**	**59.2**	

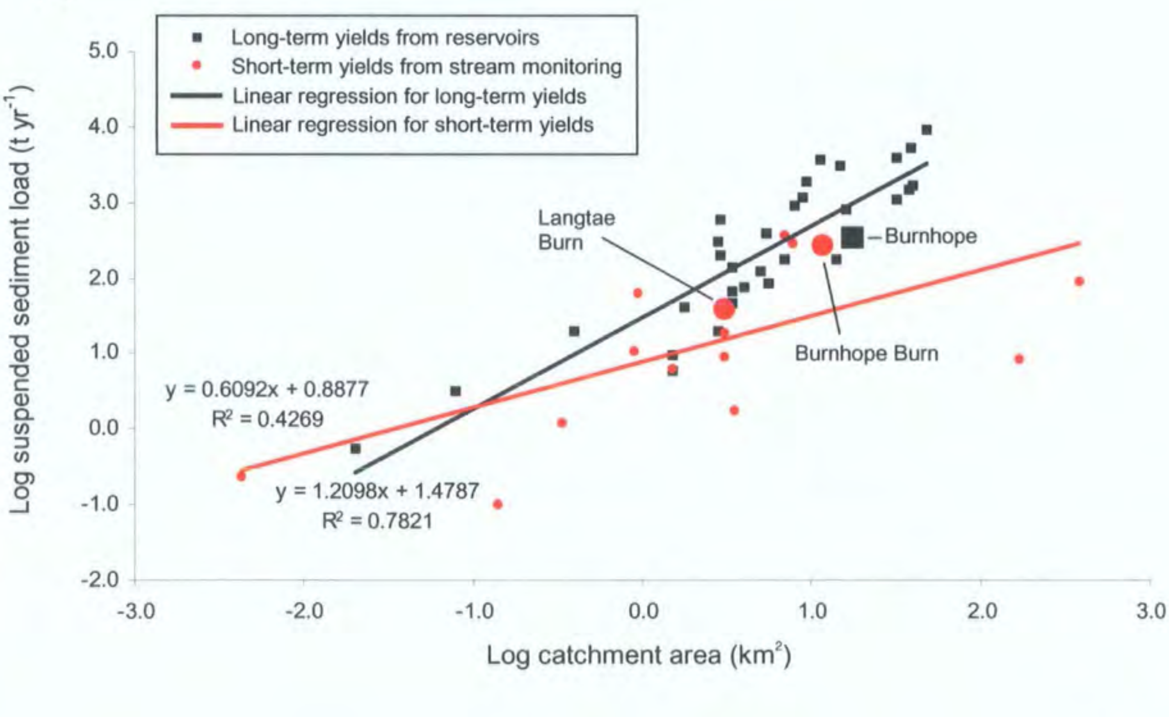
Figure 8.4 (A) Variations in annual sediment load estimates against catchment area for (a) Kinder, Bilberry and Wessenden Valley Chain, South Pennine reservoirs, (b) North Third and Carron Valley reservoir in Midland Valley, Scotland, (c) Fontburn reservoir, (d) Monachyle catchment, Wales and other upland catchments in the UK.

(B) Linear regression analysis of yields from reservoir sedimentation and stream monitoring against catchment area.

(A)



(B)



Sediment loads are primarily dependent on sediment supply, which is often not directly related to basin area. De Boer & Crosby (1996) state that there are often changes in contributions from sediment sources and the effectiveness of sediment sinks that are not reflected by the catchment area index. One of the direct influences on sediment supply is rainfall and the frequency, intensity and duration of rainfall varies temporally and spatially within and between catchments. Each of the load estimates represented on the scatterplot (Figure 8.4A) are from specific periods of monitoring over a range of timescales. These temporal issues of variation in timescales of sediment yield estimation and spatial issues of sediment sources and sinks must be considered when making comparisons on the basis of sediment load at any basin scale. Figures 8.4A and B do, however, provide a basis for comparing general sediment load relationships between the Burnhope and Langtae catchments and other published studies.

There is a general increase in sediment load with catchment area for both reservoir-based and monitored loads in these catchments (Figure 8.4B). Table 8.5 shows the regression statistics for the relationships. The steeper trend line for long-term sediment yield estimates from reservoir sedimentation (Figure 8.4A) indicates greater overall yields from studies with larger catchment areas in comparison to estimates from stream monitoring. A reason for this trend in higher yields from reservoir sedimentation could be related to the increased probability of sediment transfer from large events being recorded in reservoir sediments and also the occurrence of secondary sedimentation of material transferred through storage in a series of individual storm events. The nature of quasi-continuous stream monitoring is not conducive to recording all events, which is an issue of particular concern in upland catchments where the majority of sediment is transferred during large magnitude, low frequency events.

Figure 8.4A shows that load estimates from Burnhope Reservoir are considerably lower than those reported for moorland catchments feeding Southern Pennine reservoirs (Kinder, Bilberry and the Wessenden Valley chain, marked A on Figure 8.4A) and those in the Midland Valley of Scotland (North Third and Carron Valley, marked B on Figure 8.4A) that have catchments dominated by extensive, thick accumulations of peat (Duck & McManus, 1990). Yields from Burnhope Reservoir are most comparable to the forested catchments feeding Fontburn Reservoir (marked C on Figure 8.4A) and the Tweed that has a sediment load of 174 t yr^{-1} from a catchment comparable in size to Burnhope. Sediment loads from monitoring on Burnhope Burn are closely related to those recorded in the Monachyle catchment (marked D on Figure 8.4A) in the Balquhidder basins, Scotland.

Table 8.5 Regression statistics for relationship between load estimation and catchment area determined from reservoir sedimentation and stream monitoring.

Method of sediment yield estimation	No of cases	Intercept value (*a*)	Slope value (*b*)	R^2	t-value*
Reservoir sedimentation	32	1.2098	1.4787	0.78	10.32
Stream monitoring	16	0.6092	0.8877	0.43	3.23

* All values significant at 0.01 significance level (n = >15, t = 2.92)

The basin area is slightly smaller than the Burnhope catchment but has similar drainage basin characteristics and records annual loads of 292.6 t yr^{-1} (Stott *et al.*, 1986). In summary, the annual sediment yields recorded for the Burnhope and Langtae catchments are lower than the majority of published loads for upland basins based on catchment area. Specific yields for the Burnhope and Langtae catchments are 23.4 and 14.4 t km^{-2} yr^{-1} respectively, which are less than the typical suspended sediment yield supplied to British reservoirs proposed by Walling and Webb (1981a) as 30 t km^{-2} yr^{-1} and lower than the mean estimates based on published studies in Tables 8.3 and 8.4. Prior to the work on southern Pennine and Midland Valley reservoirs, sediment yields of between 10-50 t km^{-2} yr^{-1} were considered characteristic of upland catchments (Labadz *et al*, 1991) which compares to the specific yields from Burnhope and Langtae fluvial monitoring as well as estimates from reservoir accumulation of 33.3 t km^{-2} yr^{-1}.

Suspended sediment yield estimations from Burnhope Reservoir can be analysed in relation to the classification of British reservoirs proposed in the DETR report (2001) outlined in Chapter 7, Section 7.1. The classification of reservoirs in terms of sedimentation was based on a series of reservoir and catchment sediment yield delivery characteristics. Sediment yields were available for 107 British storage reservoirs providing a mean value of 84 t km^{-2} yr^{-1}. This mean value is almost three times greater than the yield estimate from Burnhope Reservoir. Table 8.6 shows the classification system of reservoir yields in terms of land use proposed in the DETR report (2001). There is a general trend of increasing sedimentation rate with land use category. The value of 33.3 t km^{-2} yr^{-1} estimated from Burnhope Reservoir fits into category 2 (upland with poor vegetation), which has a mean value of 36.8 t km^{-2} yr^{-1} and is comparable to the minimum yields in the upland peat/moorland category. This mean value for category 2 is considered as a good 'first approximation' for reservoirs in these type of catchments that are considered to be at 'medium susceptibility' to sedimentation (DETR report, 2001). The majority of data for reservoirs in category 3 (Table 8.6) are from Southern Pennine reservoirs (White *et al.*, 1996b; Labadz *et al.*, 1991) and those from upland Scotland (Duck and McManus, 1990, 1994). Sediment yields from these reservoirs are in excess of 100 t km^{-2} yr^{-1} and considerably greater than Burnhope Reservoir yields.

Table 8.6 Classification of sediment yields (t km^{-2} yr^{-1}) from small British lakes and reservoirs.

Burnhope Reservoir yield = 33.3 t km^{-2} yr^{-1}

	Category 1	Category 2	Category 3
	Upland less erodible soils or established forest	Upland poor vegetation	Upland peat/moorland
Minimum	7.0	3.9	35.7
Maximum	28.5	93.0	212.7
Median	12.5	39.0	167.0
Mean	15.4	36.8	148.0

Modified from DETR (2001) report

8.4 Evaluation of the temporal and spatial scales of catchment sediment transfer

The catchments of Burnhope and Langtae are typical of those of the North Pennine upland region with geology consisting mainly of rocks of Carboniferous limestones, shales and sandstones. The superficial layer of soliflucted boulder clay that overlies this bedrock has provided a significant source of both fine and coarse (boulders and gravels) sediment to the channel when exposed by lateral erosion. The high drainage densities in the Burnhope and Langtae catchments reflect the finely divided network of steep streams. These boulder and bedrock channels provide the dominant sediment transport pathways in the Burnhope and Langtae catchments. Channelized flow is dominant over sheet flow in performing the majority of sediment transport from upland catchments in the UK (Moore and Newson, 1986). The climate of the North Pennine region is 'upland maritime' with high annual precipitation totals. The combination of steep channel morphology and high rainfall results in a flashy hydrological regime where peaks in rainfall correspond closely to peaks in the discharge hydrograph. From contemporary monitoring of suspended sediment concentrations it is evident that sediment transfer is negligible during low discharges and the majority of sediment is transported during storm events.

Sediment transfer was found to be supply-limited in both catchments with higher sediment concentrations on the rising limb of discharge hydrographs than those at the same discharge on the receding limb. Peaks in discharge were sometimes found to precede those of concentration, which could be indicative of sediment exhaustion from the previous event. These observations can be discussed in the context of findings of Carling (1983) from investigation of suspended sediment concentrations during storm events in Carl Beck and Egglestone Beck, upper tributaries of the River Tees. These boulder-bed tributary streams drain catchments with similar geology to the study area (Carling, 1983). Peak concentrations tended to be higher on the rising than the falling limb of individual storm hydrographs from both Carl and Egglestone Beck, which is consistent with the findings from Burnhope Burn. However, the timing of peak concentration in relation to peak discharge differs with peak concentration occurring just before each peak in discharge. The dynamics of sediment transfer during a string of consecutive events in Burnhope Burn revealed that sediment exhaustion was both an intra- and inter-event condition. There was an overall decrease in suspended sediment concentration in Burnhope Burn recorded in consecutive events occurring in quick succession despite only small variations in peak discharges between events. However, when recovery times between events increased the suspended sediment concentrations increased with respect to discharge levels.

Similar findings on recovery times between events and peak suspended sediment concentrations were reported by Carling (1986b). Based on these examples, suspended sediment exhaustion is characteristic of the sediment systems in upland North Pennine catchments.

In the North Pennine region there has been evidence of human activity since the early to mid Post-glacial period (10,000 to 4000 BC). Investigation into the impact of human activities over the past 200 years in the Burnhope and Langtae catchments has highlighted the occurrence of metal mining as the dominant disturbance factor shaping the sediment transfer systems in both catchments. Surface extraction of minerals via hydraulic mining methods in tributary channels resulted in excavation of large volumes of sediment that were washed into the channel and deposited on floodplains. This flushing resulted in reworking of channel deposits and lateral erosion of channel margins altering the morphology of sections of Burnhope and Langtae stream systems. Metal mining in these catchments ceased in the early 1900s and since this time land use change and disturbance has been negligible.

The results of the geomorphological mapping of the channel networks (Chapter 5) reveal that the majority of the features formed during the mining period have revegetated and the channel system has stabilised. However, these deposits are currently being locally reworked as the channel impinges on channel banks and side slopes. Stream-side scars and cut banks are the dominant sources of fine and coarse sediment (boulders and gravels) with some coarse sediment being eroded from the bedrock channel during high magnitude events. Pathways of coarse and fine sediment transfer from these sources has been expressed in a conceptual model (Figure 5.4) and field observation has revealed exposed, reworked mining sediments overlaying fluvial material in Burnhope Burn and soliflucted boulder clay deposits overlain by blanket peat in Sally Grain (Figure 5.13).

The spatial variability of sediment sources in the study area was analysed in terms of stream classification. In the Burnhope catchments, 94% of scars were located in 1st order tributaries compared to 65% in the Langtae system. A larger percentage (35%) of scars were recorded in Langtae Burn in comparison to Burnhope Burn which are both second order streams. This may be the result of Langtae Burn being more laterally confined in its lower reaches. These issues of channel confinement can be extended to the discussion of spatial variability and frequency of cut banks in the study area. The frequency of cut banks to channel length in the Langtae system was also found to be greater than in the

Burnhope system and is possibly the result of channel confinement. However, without data on the basal lengths of cut banks in the Langtae system comparison cannot be made regarding sediment supply potential from cut banks between the Burnhope and Langtae systems. Comparing the relative importance of stream-side scars to cut banks in terms of basal length connectivity and subsequent sediment supply to the stream in the Burnhope system, revealed that distinction could be made between the first and second order streams. The ratio of channel length to basal length of cut banks in Burnhope Burn was higher than the ratio of channel length to basal length of stream-side scars. A possible explanation for this is the decrease in channel confinement downstream so that the second-order channel impinges in the hillslopes less but there is a greater tendency towards lateral migration and stream bank erosion downstream. The distinction between basal length of scars and cut banks to channel length in the first order streams is less significant. However, based on the ratio of channel length to basal length of both features, stream-side scars are the greatest potential sources of sediment to first order channels.

Evidence from field observation (geomorphological map Figure 5.1) reveals fine sediment storage on channel banks, bed and as overbank deposits. During low flow there is negligible supply of fine sediments in the active channel due to exhaustion of the available sediment during the previous event. There is no fine sediment supply until the discharge levels increase on the rising limb of the next storm event causing bed disturbance and actively eroding exposed fine sediments on stream-side scars and channel banks. As discharge levels decrease on the receding limb of the hydrograph, erosion ceases and as discharge reaches pre-event levels any remaining fine sediment has been washed through the system. In relation to the sediment transfer system of Carl and Egglestone Beck (Carling, 1986b) discussed previously, the minor contradiction between the timing of peaks in concentration and discharge in the two studies could be related to in-channel sediment storage and the timing of sediment supply. In Burnhope and Langtae channels the supply from fine sediment from storage appears more easily exhausted than the supply of fine sediment from the matrix material of the channel bed in Carl and Egglestone Beck (Carling and Reader, 1982). These minor variations between similar catchment systems reveal the complexities inherent in modelling sediment transfer in drainage basins.

The transfer of bedload (boulders and gravels) occurs when threshold discharges are reached during a storm event. Boulder and gravel sediments stored in the active channel are reworked while new sediments are supplied from lateral erosion of stream-side scars and cut banks. These sediments are transferred through a series of storage zones and numerous mid-channel, lateral and over bank boulder-gravel berms, and benches are evident along the channel networks in both catchments. Field observation and air photograph interpretation revealed that the location of boulder deposits relative to the channel network varied with distance downstream. In headwater reaches, deposits were located in the active channel while further downstream as the channel widened there was an increase in valley floor storage potential.

Dating of these deposits using lichenometry established a chronology for determining temporal scales of boulder transport in Burnhope and Langtae Burn. The results revealed that there was no downstream trend in substrate age. The range of age estimates was fairly evenly distributed downstream in both catchments, indicating that these deposits had been formed by a number of flood events over time. The majority of deposits in the Langtae catchment were dated within the last 20 years while those from Burnhope spanned the last 100 years. The lack of older deposits in Langtae could be linked to confinement, with the majority of deposits being restricted to storage in the active channel. There is a general lack of detailed flood data for sparsely populated headwater catchments, which results in the geomorphological effectiveness of storms events in this region being poorly documented (Carling, 1986b). However, the geomorphological impact of a storm event that occurred on the watershed between upper Teesdale and Weardale in the North Pennines on 17th July 1983 (Carling, 1986b) can be used as an analogue for the Burnhope and Langtae catchments.

Carling (1986b) reports on the geomorphological response of channel networks and valley bottoms in three small catchments of Langdon Beck, Ireshope Burn and West Grain all located south of Burnhope reservoir. Complete evacuation of deposits in upper reaches of the channel was noted together with severe erosion of the shale bedrock with boulders plucked from jointed limestone. Till slopes along channel margins were undermined and in the downstream channel reaches or where the channel was less confined, gravels were deposited in the form of boulder berms both along and over channel banks. In the lower reaches chutes were cut across channel bends forming storm channels and fine peat, sand and silt deposits were absent immediately after the flood (Carling, 1986b). Each of the geomorphic impacts noted by Carling (1986b) can be related to the findings from field observation (geomorphological mapping) and stream monitoring in the Burnhope and Langtae systems. The complete evacuation of channel deposits in the headwater reaches of the channels described by Carling (1986b) can be related to the reworking of boulder deposits in Langtae Burn while the undermining of till slopes along the channel can be related to the supply of fine and coarse grained sediment from stream-side scars and cut banks. Despite the close proximity of this storm event to the study catchments, the catchments were on the edge of the event and runoff to the reservoir from the catchments as a result of the intense rainfall was small.

Despite these findings, daily rainfall totals recorded at Burnhope Reservoir on 17th July 1983 were the fifth highest on record since 1936 (Table 5.6). No formal observations of the geomorphic impact of this event were made in the Burnhope or Langtae catchments and the intensity or duration of the rainfall is not known. However, based on sediment loads determined from contemporary storm monitoring it may be assumed that an event of such magnitude would have mobilised sediment from the catchment to the reservoir. Therefore, the geomorphic impact of a particular event can vary between catchments and subsequent events can have a contrasting geomorphic impact from the previous event of a similar magnitude. Analysis of patterns of sediment transfer and total suspended sediment loads of contemporary storm events in the Burnhope catchment revealed distinct variations in the both the timing and magnitude of sediment transported. The characteristics of each storm event varied in terms of magnitude and frequency and this is reflected in the geomorphological impact of each individual event.

An example of the variations in geomorphological impact of storm events on the sediment transfer systems of upland catchments has been provided by Newson (1980a). Analysis of two storm events that occurred in the Plynlimon study catchments of the Severn and Wye in mid-Wales in August 1973 and 1977 revealed the variation in storm characteristics between these convective events. Widespread heavy rainfall over a period of six hours that evenly effected the Severn and Wye catchments fell in August 1973. Conversely the 1977 event was a highly localised thunderstorm that occurred over the Severn catchment and had a duration of 2 hours (Newson, 1980a). The geomorphic effectiveness of the events also differed with the first (1973) resulting in slope failure and the supply of sediment to the system from hillslope sources while the second (1977) concentrated on changing channel morphology through erosion and deposition (Newson, 1980a). These distinctive variations in the impact of storm events on sediment transfer highlight the complexities inherent in predicting sediment transfer from analysis of individual historical storm events.

These examples of the geomorphic impact of storm events in the North Pennines (Carling, 1986b) and mid-Wales (Newson, 1980a) have provided a context for the seasonal evaluation of the sediment transfer system of Burnhope and Langtae catchments. Both the examples were summer convective storm events with rainfall of 'very rare' intensities (Newson, 1980a; Carling, 1986b). It is important to recognize that sediment transfer is not restricted solely to the seasons with highest monthly rainfall totals (October-March). Often a disproportionately large volume of sediment can be transferred during the driest months of the year as a result of these convective storm events. The results of seasonality analysis on suspended sediment concentrations from Burnhope Burn revealed an overall trend of peak concentrations during the winter months with troughs during the summer months. These variations in suspended sediment concentration are linked to overall discharge levels that are in turn controlled primarily by rainfall patterns. Convective summer storm events are overlooked when analyzing suspended sediment concentration data over annual timescales and the short storm durations make them easily missed by stream monitoring programmes. Burnhope Reservoir is the predominant storage zone of fine sediment eroded from the catchment and unlike stream monitoring, records fine sediment yields from all storm events supplying sediment to the reservoir. Analysis of the sedimentological character of core samples taken from the reservoir is discussed in relation to longer-term variations in climate and reservoir water level fluctuations in the next section of this chapter.

8.5 Evaluation of sediments in storage in relation to climate change and reservoir water level

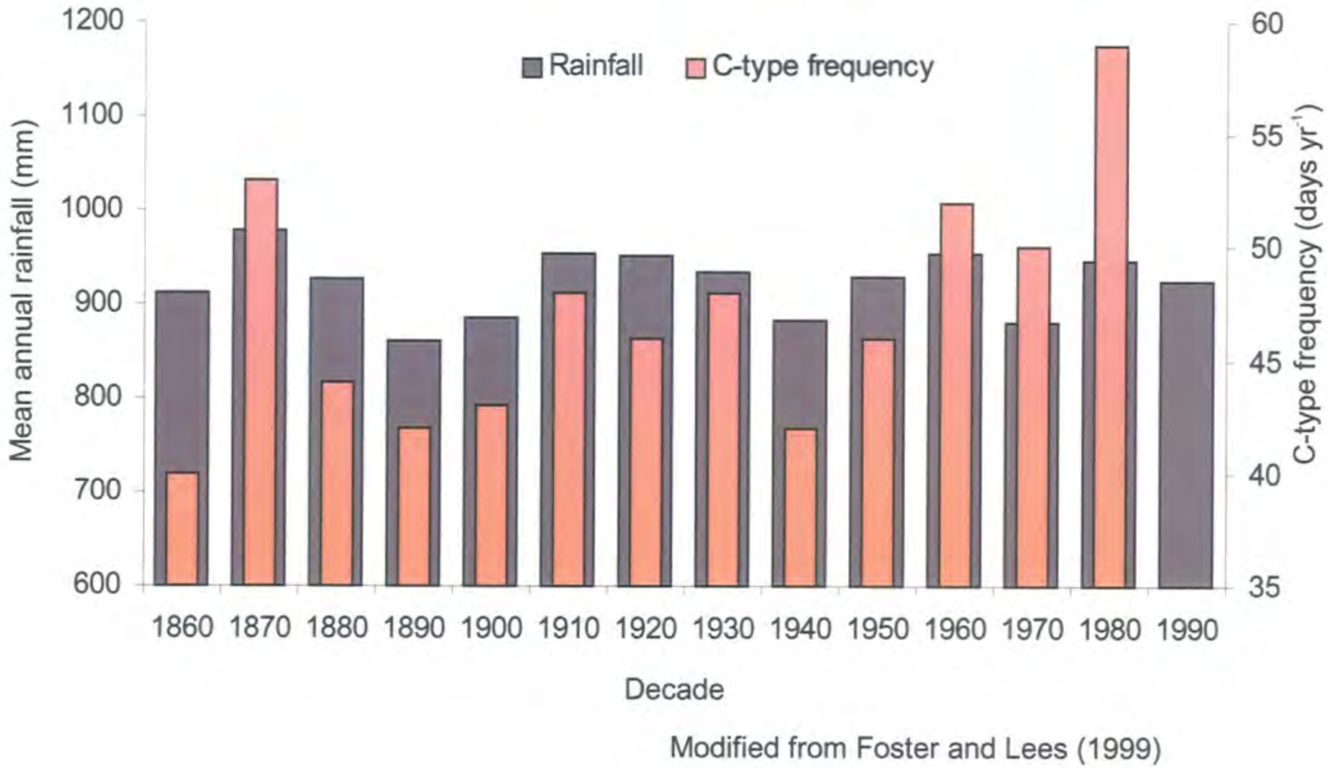
Analysis of sedimentation from Burnhope Reservoir has provided mean annual sediment yield estimates, information on the spatial distribution of sediment in the reservoir and evidence of the geomorphic impact of recent climate change on the sedimentological character of reservoir sediments (Chapter 7). Estimates of mean annual sediment yields have been expressed in the framework of the reservoir sediment budget in section 8.2. In this section potential links are made between variations in rainfall and the sand-sized layers identified from particle size analysis and radiometric dating of core sediments.

Dating of cores 1 and 8 using ^{137}Cs provided estimates of sediment accumulation since impoundment in the distal and proximal sections of the reservoir. When trends in ^{137}Cs content of core sediments were compared to the record of fallout in the Northern Hemisphere (after Cambray *et al.*, 1987) down-core trends in both cores conformed to the classic shape relating to atmospheric fallout in the Northern Hemisphere (Figure 4.5). The 1959 and 1963 peaks in fallout are evident in both cores. This provided an ideal opportunity for dating the particle size record. The onset of sand-sized layers in both dated cores occurred in the mid-1970s and core correlation provided evidence that the timing of the deposition of these layers corresponded between cores (Figure 7.22).

Analysis of the ^{137}Cs record in sediments from Blelham Tarn in Cumbria revealed that the ^{137}Cs inventory was derived from input of allochthonous sediments in the form of catchment soils enriched in fallout ^{137}Cs. This theory was supported by evidence of the magnetic properties of the core sediments that pointed to rapidly accelerating soil erosion within the lake catchment, which was tentatively related to increased sheep stocking densities. These examples of lake and reservoir sediments with disturbed ^{137}Cs inventories are from catchments with recent records of land-use change and disturbance. In the Burnhope Reservoir catchment there has been negligible land use change and disturbance in the recent past, which is supported by the classic form of ^{137}Cs inventories in cores from the reservoir. On this basis attention was concentrated on climate change and issues of reservoir operations as the two key variables influencing the onset of the deposition of sand layers in the reservoir in the mid-1970s.

Analysis of long-term daily rainfall records revealed the onset of diverging winter-centred and summer-centred rainfall totals from the mid-1970s onwards with wetter winters and drier summers. These trends are consistent with rainfall patterns over the United Kingdom for the same time period as reported by Jones and Conway (1997) and Marsh and Sanderson (1997). Further investigation into recent climate change by Wilby *et al.*, (1997) using the Lamb (1972) catalogue of daily weather types has revealed variations in the frequency of winter weather patterns since the late 1970s. The Lamb (1972) catalogue of daily weather types is a classification system that provides a daily record of surface pressure patterns across the British Isles since 1861 (Wilby *et al.*, 1997). This daily classification includes cyclonic, anticyclonic, westerly, northerly, southerly and 29 other weather types that include temperature, rainfall and potential evaporation. Figure 8.5 is modified from Foster and Lees (1999b) and compares trends in annual rainfall totals on a decadal basis from 1860 to the 1990s and daily frequency of winter cyclones (Lamb C-type weather frequencies) in England and Wales from the 1860s to 1980s. Mean annual rainfall has varied on a decadal basis but there are no distinct trends in the data.

Figure 8.5 Trends in daily Lamb C-type weather frequencies and annual rainfall totals for England and Wales (1860-1990 by decade, modified from Foster and Lees, 1999).



When comparing mean rainfall totals with frequency of days recording C-type weather patterns, again there are fluctuations in the data but there is a similar pattern between the variables up until the 1960s (Foster and Lees, 1999b). From the 1960s to the 1990s there is a significant divergence between the variables with the 1980s recording the maximum number of days with winter cyclones on record (Foster and Lees, 1999b). The increase in frequency of winter cyclones in the 1980s corresponds to the diverging rainfall patterns identified in the Burnhope rainfall record and over England and Wales in general (Jones and Conway, 1997; Marsh and Sanderson, 1997). It must be stressed, however, that the data in Figure 8.5 are mean values for England and Wales and there are no allowances made for any variations in the frequency of winter cyclone weather patterns in upland and lowland regions.

Since recent land use change in the Burnhope and Langtae catchments has been negligible the evidence suggests that that the catchment sediment yields have responded to variations in the climatic signal with the onset of diverging rainfall patterns and the frequency of winter cyclones. From correlation between sediment yield estimates from four catchment studies from a range of locations in the British Isles and the various Lamb (1972) Weather Types, Wilby *et al.* (1997) found that a significant proportion of long-term variability in sediment yields could be related to variations in the frequency of winter cyclones. The frequency of winter cyclonic conditions (C-type weather patterns) produced a stronger correlation with sediment yield compared to total rainfall, which suggests that C-type weather patterns could capture additional relevant information such as frequency of extreme events, storm intervals times, antecedent soil moisture conditions and rainfall intensities or storm duration (Wilby *et al.*, 1997). With the significant increase in frequency of winter cyclones in the 1980s, Foster and Lees (1999b) reported the significant increases in sediment yield during the 1980s at Silsden and Fontburn, reservoirs, Elleron and Fillingham lakes and Newburgh Priory Pond all located in LOIS (Land Ocean Interaction Survey) catchments along the east coast of England from the Tweed to the Trent. These increases in sediment yield were attributed to increased frequency of winter cyclonic conditions (Foster and Lees, 1999b). As the increase in sediment yields in the LOIS catchments have been attributed to the frequency of winter cyclonic conditions it is proposed that the deposition of sand layers in Burnhope Reservoir can also be attributed to changes in climatic conditions.

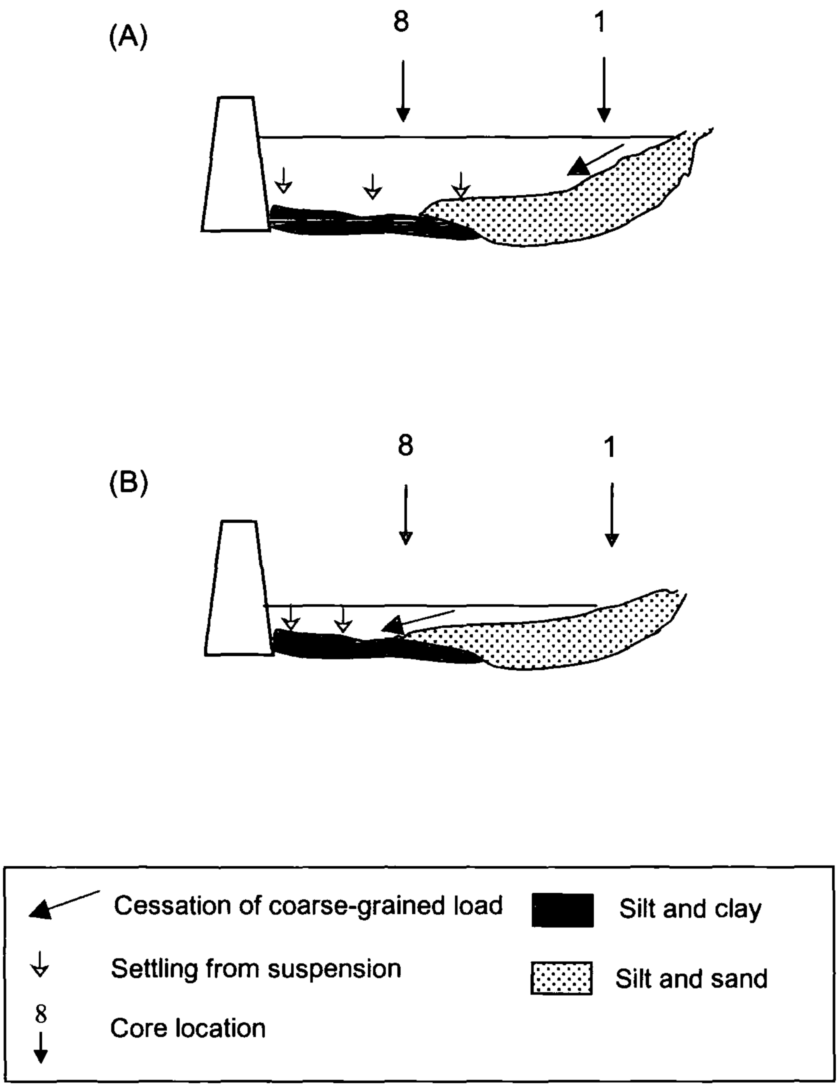
Based on the principle that climate is the primary control on the demand for water from Burnhope Reservoir, corresponding variations in rainfall and water levels were predicted.

Rapid fortnightly increases in reservoir levels have been related to periods of maximum divergence between winter-centred and summer-centred rainfall totals and the occurrence of minimum reservoir levels are linked to periods of summer drought in the early and late 1980s and early 1990s. The linkages between variations in rainfall records, reservoir levels and the onset of sand-sized particle deposition from the mid-1970s onwards enable conceptual models of sediment deposition to be developed.

The location from which sediment cores were taken in relation to the proximal and distal sections of the reservoir is fundamental in terms of assessing the environment of deposition of these sand-sized layers. Figure 8.6 shows a conceptual model of the location of deposition of the coarse-grained (sand) fraction of suspended load in Burnhope Reservoir at full capacity (scenario A) and during a draw-down event (scenario B). The coarse-grained fraction is deposited in the proximal section of the reservoir during scenario A. For sand particles to reach the distal section of the reservoir, water levels must be drawn down as show in scenario B. During this draw down period sediments in the proximal section of the reservoir are exposed and no sediment deposition can take place. This evidence suggests that it is unlikely that the layers in core 1 and core 8 were deposited during the same event. The layers in core 1 must have been deposited during scenario A of Figure 8.6 when this section of the reservoir was inundated.

One of the few studies that considers variations in reservoir water level as the key factor controlling the spatial deposition and sedimentological character of reservoir sediments was carried out by Laronne (2000) in the Yatir Reservoir located in the semi-arid southern region of Israel. Laronne (2000) investigated sedimentary event couplets deposited by runoff events entering the Yatir Reservoir. The clastic rhythmites deposited in the ever-emptying Yatir Reservoir were described as consisting of two sedimentary singlets, the bottom layer, namely the traction load consisting of coarse silts and fine sands deposited by cessation of flow entering the reservoir and the top layer of finer silts and clay deposited by settling from suspension. Analysis of the spatial distribution of sedimentation in this reservoir through correlation of these individual event rhythmites lead to the development of a conceptual model of the differences between suspended sediment deposition in an ever-emptying and an ever-full reservoir. When flow enters a reservoir containing water (classed as an ever-full reservoir) the suspended load divides upon impinging into the still water body, the coarser suspended sediment depositing in the proximal section of the reservoir while the finer fraction remains in the water body until the water is quiescent (Laronne, 2000). The coarser fraction cannot penetrate deep into the reservoir (unless

Figure 8.6 Conceptual models of the location of deposition of coarse-grained sediments in Burnhope Reservoir at (A) full capacity and (B) during a draw down event.



Modified from Laronne (2000)

transported by a high velocity jet stream) due to the loss of velocity but the finer sediment fraction can be deposited ubiquitously (Laronne, 2000). When flow enters a dry reservoir (or reservoir in draw-down) the coarser suspended fractions are transported deeper into the distal part of the reservoir and only deposited when the inflow impinges on standing water. Despite this conceptual model being developed based on analysis of reservoir sedimentation in a semi-arid region, the model proposed by Laronne (2000) provides context for the conceptual model developed for sand layer deposition in Burnhope Reservoir.

Evaluating the potential sources of sediment in these sand-sized layers in Burnhope Reservoir results in three possible scenarios:

1. The sand was transported from the catchment during a storm event
2. The sand was reworked from erosion of pre-impoundment channels by storm flow during a period of draw-down (in the case of core 8)
3. The sand is sourced from the slumping of sediments from the steep peripheral slopes of reservoir when water levels are drawn down.

Considering the sand layers in both cores, scenarios 1 and 2 could be interlinked. Storm flow enters the reservoir basin during draw-down carrying suspended sediment from the catchment. This flow then reworks sediment from the proximal limb of the reservoir and the sediment load is deposited when the carrying capacity decreases when flow impinges on the reservoir water body. Scenario 3 is only applicable to describing the environment of deposition in core 8 but based on the idea that deposition of sand on steep slopes of the reservoir is unlikely this scenario of sediment slumping is improbable. A combination of scenarios 1 and 2 is the most probable source of sediments in these sand layers that are moved during storm events.

The work of Curr (1995) on coarse-grained sediment layers (>45 μm) from a small ornamental lake draining the agricultural Corston Brook catchment in the UK is the closest example to the present study available on the analysis of coarse-grained layers in relation to rainfall records in the UK. Analysis revealed that the layers in Corston Lake were poorly sorted and this was attributed to variations in the magnitude and turbulence of the transporting flood events. A simulated model of stream response from daily rainfall records was developed and compared to particle size analysis from the lake core in an attempt to determine core chronology. Correlation between peaks and troughs of stream response and coarse-grained layers produced a coefficient of 0.953 (Curr, 1995) and this close correspondence enabled successful dating of the core sediments. The conclusions suggested that events of moderate magnitude and frequency were the most influential in sediment transport in the Corston catchment.

The scale and bathymetry of Burnhope Reservoir and Corston Lake are very different and this must be acknowledged when considering the controls on sedimentation in these different water bodies. The sand-sized sedimentary layers in Burnhope Reservoir are not as distinctive as those from Corston Lake, which could be related to the variations in sediment load, transport and availability in upland moorland and lowland agricultural catchments. Mean annual sediment loads for Corston Lake based on approximately 218 years of sedimentation was 111 t which compares closely to monitored transport rates for the 1977-1979 period of 99.7 t yr^{-1}, or 25 t km^{-2} yr^{-1} (Curr, 1995). These specific yields compare to those from stream monitoring at Burnhope Reservoir (38.8 t km^{-2} yr^{-1}) so variations in stratigraphy are not necessarily related to variations in total annual sediment load. It appears that these variations are related to the location and nature of sediment sources. Curr (1995) commented on water logging of catchment fields during the winter months, reducing vegetation cover and promoting soil erosion. During storm events, overbank flow resulted in overland flow in these fields providing sediment for transport to the reservoir. In the Burnhope catchment the main sources of sediment are channel based stream-side scars and cut banks that may require active erosion on the rising limb of a storm event for sediment transport to occur. Variations in water level must also be considered in comparison of the stratigraphic records. Periods of distinct reservoir draw down are recorded for Burnhope Reservoir, while only a gradual shallowing of Corston Lake is recorded from over 5 m in depth to 2 m in 218 years (Curr, 1995). Variations in water level results in discontinuity of reservoir sediments as revealed by analysis in the Burnhope study. The deposition of sand-sized layers at Burnhope has also been related to the onset of diverging winter and summer rainfall totals that may have activated sources not previously activated, or may be linked with reservoir fluctuations as a combined causal factor for coarse-grained sediment deposition in Burnhope. The variations in the stratigraphic records between upland and lowland water bodies in this example appears to be related to the variations in sensitivity of catchments to variations in rainfall patterns, the nature of sediment sources and variations in water level.

The present study is the only example of research into the sedimentological character of sediments in relation to climate change in the UK uplands. Reservoir water level fluctuations have added an element of complexity into reconstructing the geomorphic impact of recent variations in climatic conditions on suspended sediment transfer in Burnhope and Langtae catchments. This study has monitored the response of sediment delivery in two North Pennine upland catchments to contemporary climatic conditions and evaluated the response of the sediment delivery system to recent fluctuations in rainfall patterns since the late 1970s. On the basis of this understanding the possible impacts of future climate change on sediment delivery in upland catchments may be discussed.

8.6 Future climate change in relation to sediment delivery in upland catchments of the UK

The next hundred years climate is expected to change more rapidly than ever before (Eybergen and Imeson, 1989). If this statement is true, then it raises an important research question: what impacts will these climatic variations have on processes of sediment production, transfer and deposition operating in upland catchment systems? In part, the answer to this question lies in establishing what influence past variations in climate have had on the sediment system and by reviewing some of the past trends in climatic geomorphology there is a possibility for evaluating the response of geomorphological processes to future changes in climate variables (Eybergen and Imeson, 1989).

A comprehensive review of the potential impacts of climate change on a global scale by the Inter-governmental Panel on Climate Change (IPCC, 1996) predicts increased precipitation leading to increased runoff in higher latitude regions, changes in flood frequency especially in northern latitudes and an increase in the frequency and severity of drought events due to changes in precipitation and evapotranspiration. Predicting the impact of climate change at smaller spatial scales requires regional level scenarios, which are based on uncertainty. Mitchell and Hulme (1999) suggest using multiple forcing scenarios to cope with global system unpredictability as opposed to using conventional methods of predicting climate change based on a single result predicted by a single global climate model (GCM) with numerous deficiencies. These findings basing climatic prediction on multiple forcing scenarios using a number of GCMs are supported by recent research by Prudhomme *et al.* (2003). The largest uncertainty in climate prediction in five UK catchments (The Greta, Rea and Beult catchments in England; The Wye in Wales and Hallandale in Scotland) was attributed to the type of GCM used and it is therefore essential that climate change impact studies consider a range of climate scenarios derived from different GCMs (Prudhomme *et al.*, 2003). Predictions of the possible impacts of future climate change on sediment delivery systems in upland catchments are based on the uncertainties inherent in predicting regional climate change.

The emerging consensus amongst the scientific community on future climate and hydrology of the UK is characterised by increased winter rainfall and flooding, plus the likelihood of summer droughts and intensified storm activity (Beven, 1993; Wilby, 1995). Harvey (1991) considers the implications that climatically-induced changes in hillslope stability, storm event frequency and hillslope-channel coupling will have on sediment supply and resulting channel morphology and stability in upland streams of the Howgill Fells, northwest England. He concludes that the most important potential effect of climate change will be magnitude and frequency characteristics in relation to erosion threshold events and system recovery time. In the event of increased frequency in winter storm events, the nature of the sediment supply system in upland channels could be altered with the sporadic nature of sediment transfer being smoothed by the regular supply of sediment. If the magnitude of events increases there may be more channel erosion and incision increasing the amount of sediment available for transfer. If the increase in magnitude is coupled with an increased frequency of events, then sediment exhaustion could intensify as the system reaches a state of equilibrium.

All these changes are dependent on the thresholds of erosion, landscape sensitivity and capacity of flow in individual catchments. The thresholds of erosion of sediment on channel banks and floodplains and are susceptible to variations in vegetation cover. If the density and or extent of vegetation on a surface increases then the thresholds of stability of that surface also increases. Un-vegetated surfaces are exposed to erosion by surface wash and more susceptible to variations in rainfall intensity whereas once a surface has a degree of coverage the surface is then protected from erosion. Research into re-vegetation of gully systems at Moor House in the North Pennines has revealed that erosion has decreased with an increase in re-vegetation (Clement, 2001).

The influence of large-scale upper atmospheric circulation patterns on the geomorphic processes operating in upland catchment systems of Northern England has been considered (c.f. Rumsby and Macklin, 1994). Investigation into the timing, nature and magnitude of river response in upland, piedmont and lowland reaches of the Tyne basin in relation to high frequency changes in climate and flood regime has revealed that channels and floodplains within the Tyne basin responded to relatively abrupt, short-term (10-30 year) shifts in hydroclimate over the last 290 years (Rumsby and Macklin, 1994). Channel accretion was noted as a result of increased frequency of moderate flooding (5-20 years) and on the basis of these historical responses to climatic fluctuations, predictions that the system will be equally responsive to future climate changes were suggested (cf. Rumsby and Macklin, 1994). However, uncertainty surrounding the prediction of regional scale temperature and rainfall magnitude and frequency, has resulted in wide ranging estimates of potential hydrological change.

Other areas in upland Britain could be vulnerable to similar responses to climate change and sediment delivery. Harvey (1991) claims that the most susceptible areas in terms of sediment yield variations, channel change and sediment delivery are those in Northern Britain that experience high precipitation and some winter snowfall. These areas are topography characterised by steep valley-sided slopes and large volumes of Devensian glacial sediments transported by late glacial solifluxtion and include the Lake District and the Pennines. A number of the more recent studies in North Pennine catchments have considered the current and future implications of variations in the climate on channel change (Warburton and Danks, 1998), peat hydrology (Burt *et al.*, 1998; Evans *et al.*, 1999) and integrated catchment management (Burt *et al.*, 1997). Despite identifying the Pennines as particularly vulnerable to the effects of climatic change (Harvey, 1991), there has been little research into contemporary and historical sediment delivery systems of North Pennine regions.

The impact of future climate change on the sediment delivery systems of Burnhope and Langtae can be discussed in the context of the predictions made by Harvey (1991) and results of the current study. Increased winter rainfall intensities together with an average increase in winter temperature will have a combined impact by increasing erosion thresholds through re-vegetation and increasing erosion potential through increased stream velocity. One scenario could be variations in the nature of sediment transferred with coarser sediments being mobilized by stream-flow and transported further supporting the theory of increased sand being deposited in the reservoir over recent timescales. A second scenario could be the increase in flood magnitude resulting in enhanced vertical channel incision and reduced lateral erosion with contemporary sources on channel margins gradually re-vegetating and stabilizing.

The lack of detailed information on the impact of climate change on past and contemporary sediment transfer together with the uncertainties inherent in establishing regional climate change prediction models create problems in assessing the likely response of upland catchments to future climate change.

8.7 Chapter summary

This discussion chapter has presented the findings of a sediment budget investigation into sediment supply, transfer and deposition in two upland catchments. The dominant inputs to the budget are the major streams of Burnhope and Langtae and reservoir shoreline erosion. Sediment yield estimates determined from stream monitoring and reservoir sedimentation contribute to the database of yields from upland rivers in the UK. Analysis of the spatial and temporal scales of sediment transfer in the major input streams has provided context for understanding the impact of climate change on sediment transfer.

Quantitative and qualitative analysis of sediment stored in Burnhope Reservoir has provided yield estimates and evaluation of the sedimentological character of deposits respectively. When placed in the context of previous published studies it is evident that while no examples of studies in other North Pennine reservoirs exist, the annual reservoir sediment yields from Burnhope are comparable to those from other upland regions of the UK. The lack of comparable studies that relate variations in the sedimentological character of deposits to climate change can be related in part to the lack of catchments that remain undisturbed by land use change, to limited resolution due to low sedimentation rates and to the scarcity of reservoirs in the North Pennines.

In conclusion, Foster (1995) noted that a combination of bottom-sediment analysis with the catchment monitoring approach appears to provide a powerful conceptual and methodological framework for an improved understanding of drainage basin catchment sediment dynamics. The combined approach of determining sediment yields from bottom sediment analysis and stream monitoring in a sediment budget framework for the Burnhope catchment has revealed the importance of shoreline erosion and storage. The selective storage of coarse-grained sediment as shoreline toe deposits and transfer of fines to deep-water storage is an important finding when catchment sediment yields are determined from bottom sediments. The sediment budget framework provides an integrated approach to quantifying sediment loads while establishing a temporal and spatial understanding of the input, storage and output components of the catchment sediment delivery system that cannot be achieved from yield estimates alone.

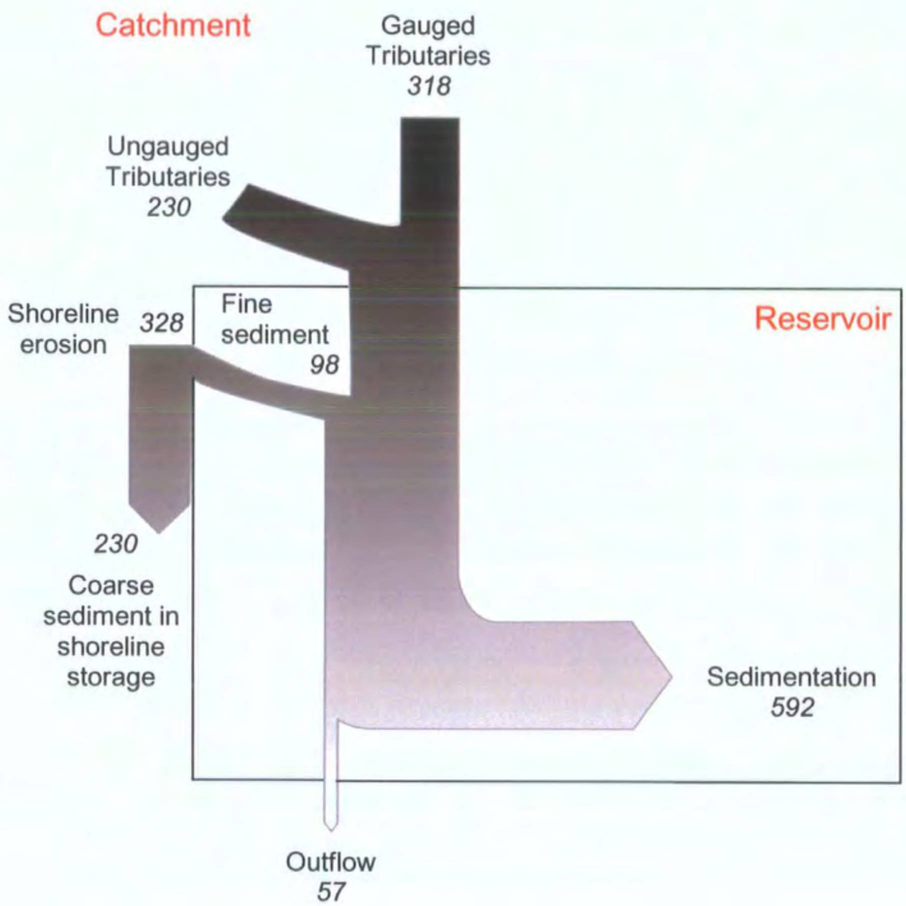
CHAPTER 9 - CONCLUSION

9.1 Summary of findings

This research has investigated sediment delivery in a North Pennine upland catchment through identification of sediment sources and sinks and quantification of sediment loads. A fine sediment budget has been developed for Burnhope Reservoir using sediment yield estimations from short-term monitoring of major tributaries, which form the dominant input component to the reservoir. Reservoir shoreline erosion is a significant input to the budget however, shoreline storage of the coarsest fraction of eroded bank material results in only 30% of total eroded material entering the reservoir. Sediment yields determined from long-term records of sedimentation in the reservoir represent the storage element of the budget. Sediment inputs from small, ungauged tributaries are not measured and represent the residual component of the sediment budget. This residual has been estimated via the subtraction method. Figure 9.1 is a sediment flow diagram that identifies and quantifies sediment loads from the catchment to Burnhope Reservoir. Sediment influxes from tributary streams are the dominant sources of sediment to the budget with 318 and 230 t of sediment coming from the gauged and ungauged tributaries respectively. Shoreline erosion contributes 328 t of which 230 t are held in shoreline storage and 94 t form part of the fine sediment storage in the reservoir.

Together with the quantification of sediment loads in the reservoir sediment budget, sediment transfer in Burnhope and Langtae Burn has been investigated on seasonal and event-based timescales. Relationships between sediment transfer, rainfall and discharge for individual events have revealed information on the magnitude and timing of sediment movement. Geomorphological mapping of potential sediment sources and sinks in the Burnhope and Langtae catchments has demonstrated little connectivity between sediment sources and the channel during low flow, which corresponds to the negligible sediment yields determined from stream monitoring at low discharges. To investigate potential variations in catchment sediment transfer over longer timescales (1936-1998), physical and radiometric analysis (^{137}Cs) of reservoir sediments has been carried out. Dating of core sediments using ^{137}Cs has enabled sedimentation rates to be estimated, annual sediment yields for the reservoir storage component of the sediment budget to be determined and sediment cores correlated. Variations in the particle size record of core sediments reveal an overall coarsening of particles in the

Figure 9.1 Sediment budget identifying sediment transfer pathways and quantifying sediment loads from the catchment to Burnhope Reservoir (t yr^{-1}) for the study year 2000-2001.



last 30 years. The timing of this increase in coarse-grained sediment flux to the reservoir corresponds to periods of diverging trends in winter-centred and summer-centred rainfall totals, which suggests that the influx of sand-sized sediment in cores is related to reworking due to variations in water level or to flushing of sediment from the catchment during wetter winter conditions, particularly when these follow dry summers.

The major findings of this study are now summarised with respect to the objectives outlined in Chapter 1.

1) *To use a rapid assessment approach to identify potential sources and stores of sediment in the study catchments and apply an absolute dating technique to provide an historical assessment of sediment transfer.*

Identifying potential sources and stores of sediment in the stream systems has provided an historical assessment of sediment transfer in the Langtae and Burnhope systems. This assessment has enabled the impacts of catchment disturbance (in particular mining activities) on sediment supply and transfer in channel systems to be evaluated. Field mapping of catchment sediment sources revealed the dominant sources were those resulting from lateral erosion at the channel margins. Exposed stream-side scars and cut banks are susceptible to erosion during high-discharge events. Blue/grey boulder clay and overlying blanket peat are the dominant exposed sediments at the very head of the main channel and in the tributary streams in the Langtae and Burnhope catchments. Soliflucted material composed of boulder and gravel deposits embedded in a matrix of fine sediments and reworked mining deposits are dominant further downstream. During low flow the majority of sediment sources are unconnected to the channel and the system remains uncoupled until discharge levels rise and activate sources linking erodible sediment to the channel system. The relative importance of stream-side scars to cut banks can be compared in terms of basal length. Based on the ratio of channel length to basal length, stream-side scars are the greatest potential sources of sediment in first order channels. The ratio of channel length to basal length of cut banks in Burnhope Burn is higher than the ratio of channel length to basal length of stream-side scars indicating cut banks as being the dominant source in the second order channel. The total surface area of scars is 51% greater in the Burnhope than the Langtae system, which is related to the basal length of scars and the general size of the failures.

Mapping and dating (lichenometry) of coarse-grained deposits in the Langtae and Burnhope systems has provided information on the spatial and temporal distribution of coarse-flood deposits. Variations in mean boulder size with distance downstream revealed a general trend of decreasing boulder size with distance downstream. The greater variation in the boulder size between first and second order channels in the Langtae system have been attributed to the potential supply of suitable material from mining waste and high stream gradients in first order channels. The location of coarse-flood deposits in relation to the channel varied downstream with deposits located in the active channel in headwater reaches and along channel margins as the area of potential storage increased with distance downstream. Dating of deposits using lichenometry revealed no distinct trends in substrate age with distance downstream in both catchments. It was therefore concluded that the deposits had been formed by a number of flood events over time. Absolute age estimates of deposits were based on a growth rate of 0.39 mm yr^{-1} determined from lichen sizes on substrates of known age. The majority of deposits have been dated within the last twenty years in the Langtae catchment and in the last 100 years in the Burnhope catchment. Variations have been attributed to greater reworking of older deposits in the confined channels of the Langtae system, re-vegetation of older deposits above contemporary channel margins and the use of *Lecanora* and *Rhizocarpon* lichens with different growth rates in the Langtae system. The age range of deposits has been compared to the Burnhope daily rainfall series. The most frequently occurring age range of deposits in the Burnhope catchment was 1976 to 1985 that corresponds to the period of higher than average annual rainfall totals. Deposits in both systems that fall outside the range of the daily rainfall record at Burnhope have been tentatively correlated to phases of increased rainfall in the Tyne basin (Rumsby and Macklin, 1994).

2) *To quantify contemporary suspended sediment yields and assess patterns of sediment transfer at different temporal scales to determine the output component of the catchment sediment system that forms an input to the reservoir sediment budget.*

Sediment yields for the periods May 2000 to March 2001 and July 2000 to March 2001 have been established in the Burnhope and Langtae catchments respectively, while patterns of sediment transfer within and between storm events were investigated for the Burnhope system in November 2000. Records of suspended sediment and discharge were combined to produce sediment-rating curves, which were bias corrected using Ferguson (1987) and Smearing correction factors. Variations were found between sediment transfer in the Burnhope and Langtae systems. In Burnhope sediment transfer occurs at a higher discharge threshold but the concentration of sediment transferred at given discharges is greater. This relates to different levels of connectivity between sediment sources and the channel in the two systems. Sediment transfer occurs at lower discharges in the Langtae system reflecting increased availability of sediment at low flow in the smaller catchment. The lack of sediment transfer at low discharges in the Burnhope system reflects the low connectivity between sediment sources and the channel at low discharges and supports the observation of sediment exhaustion on the falling limb of discharge hydrographs identified during intra and inter-storm event analysis. Comparison between hysteresis curves for individual storm events revealed different patterns of sediment transfer in relation to discharge. The relationship between suspended sediment concentration and discharge revealed that while suspended sediment transport was related to discharge, discharge levels alone were not capable of maintaining sediment concentrations. These findings correspond to those of Carling (1983) who found that sediment supply was frequently more important than hydraulic controls in regulating the output of sediment from North Pennine basins.

The influence of seasonality on sediment transfer in the Burnhope system was investigated using Fourier series analysis, by applying sine and cosine functions to cyclic patterns in time-variant discharge data. Results from regression analysis that incorporated both log discharge and sine/cosine variables revealed discharge as the most influential variable in the model but highlighted the significance of the sin/cosine variable (seasonality) in the predicting suspended sediment concentrations. Based on the significance of seasonality in the Burnhope suspended sediment system it is appropriate to consider the use of seasonal rating curves for estimating sediment loads in the Burnhope catchment. The truncated sediment-monitoring programme for the Langtae catchment has resulted in a lack of data for assessing the influence of seasonality on sediment transfer in the Langtae system. As a consequence best estimates of sediment loads from Langtae can be generated through the application of the general rating curve model and are subject to greater uncertainty.

Detailed analysis of seasonality on sediment transfer during storm events in the Burnhope catchment was restricted due to the truncated monitoring programme caused by Foot and Mouth Disease. However, detailed analysis of the relationship between suspended sediment concentration and discharge over consecutive events in November 2000 has provided valuable information on the importance of both discharge and sediment supply in sediment transfer in previously ungauged North Pennine catchments.

3) *To quantify long-term sediment yields from sediments in reservoir storage using a combined approach incorporating core depth, sediment chronology (^{137}Cs), reservoir bathymetry and aerial photography.*

Suspended sediment yields have been estimated for the Burnhope and Langtae catchments using three methods. Firstly, contemporary suspended sediment loads were estimated from monitored data as discussed in Chapter 5. Secondly, historical daily rainfall data from the Burnhope catchment for the 1936 to 1998 period is used together with contemporary rainfall-runoff and suspended sediment rating relationships to produce annual sediment yields. Finally, long-term reservoir sedimentation was used together with bulk density estimates and the ^{137}Cs chronology of core sediments, to calculate volume and mass of reservoir sediment from 1936 to 2000. Annual sediment yields recorded for the Burnhope and Langtae catchments are lower than the majority of published loads for upland basins based on catchment area. Specific yields for the Burnhope and Langtae catchments are 23.4 t and 14.4 km^{-2} yr^{-1} respectively, which are less than the typical suspended sediment yield supplied to British reservoirs proposed by Walling and Webb (1981a) as 30 t km^{-2} yr^{-1}.

Comparisons between sediment yield estimations from contemporary stream monitoring and those determined from long-term rainfall records produced comparable results for the Burnhope catchment using both seasonal and general rating curve models (17 and 33% variation, respectively). These results reflect the influence of rainfall/runoff on suspended sediment loads in the Burnhope catchment. Yield estimates from long-term rainfall records in the Langtae catchment overestimated yields from contemporary stream monitoring by 401%. This overestimation has been attributed to the calculation of long-term annual sediment loads based on average daily runoff estimates. Further analysis of storm duration in relation to sediment load estimation and the form of sediment rating curves for the Burnhope and Langtae catchments, revealed interesting variations in sediment transfer between catchments. The low slope of the general sediment-rating curve for the Langtae system results in a small range in suspended sediment concentration over a large range in discharge. In comparison, the high slope of the Burnhope rating curve and subsequent large range in suspended sediment concentration over small changes in discharge (runoff) corresponds to large changes in suspended sediment concentration. When long-term annual sediment loads in the Langtae system are calculated from daily rainfall averaged over a 24-hour period, the low slope coefficient of the Langtae regression results in sediment yield overestimates. As storm event duration decreases, the sediment load estimates for the Langtae system also decrease. The majority of storm events in upland catchments are short lived and it was concluded that lower overall estimates of sediment load for the Langtae catchment would be calculated if runoff predictions were available on a sub-daily basis.

Sediment yields from long-term reservoir sedimentation incorporate information from high-resolution core records together with low-resolution data on sedimentation distribution across the whole reservoir basin (air photographs and bathymetry). The low-resolution data could not be used to provide reliable data on sediment accumulation in Burnhope Reservoir, however, combining the techniques has enabled the active area of sedimentation in Burnhope Reservoir to be estimated. Specific annual sediment yields from Burnhope Reservoir have been estimated at 33.3 t km^{-2} yr^{-1}. When compared to the mean sediment yield of 84 t km^{-2} yr^{-1} proposed in the DETR report (2001) based on yields from 107 British storage reservoirs, Burnhope Reservoir can be considered as having below average sedimentation. When this yield estimation from Burnhope Reservoir was analysed in relation to the classification of British reservoirs (DTER, 2001). Burnhope reservoir fitted into category 2 (upland with poor vegetation), which had a mean value of 36.8 t km^{-2} yr^{-1} and a classification as being at medium susceptibility to sedimentation.

4) *To reconstruct the depositional sequence of sediments in reservoir storage and consider the extrinsic factors controlling sediment supply, transfer and deposition, evaluating the potential links within the sediment system.*

From analysis of down-core variations in physical and radiometric sedimentological parameters of core sediments, it has been possible to identify spatial variations in sedimentation in the Burnhope Reservoir basin. An overall fining of sediment from west to east has been observed from the input streams to the dam (as water depth increases). Distinctive layers of coarse-grained sediment from cores in the proximal and distal sections of the reservoir have been dated using ^{137}Cs. These coarse-grained deposits date from the mid-1970s. Investigation into the potential controls on this coarse-grained sediment deposition resulted in consideration of the extrinsic and intrinsic controls on sedimentation. The lack of disturbance due to recent land use change in the reservoir catchments suggested that analysis of long-term daily rainfall records from Wearhead Water Treatment Works at Burnhope Reservoir for the period 1936 to 1998 may reveal useful trends. A diverging seasonal trend in winter-centred and summer-centred rainfall totals from 1976 onwards was observed, with a large increase in winter and a gradual decrease in summer values. These trends in the

Burnhope rainfall data are consistent with those recorded elsewhere in the United Kingdom of wetter winters and drier summers. These fluctuations in seasonal rainfall were noted in records of water level in Burnhope Reservoir. Comparisons between particle size records of dated cores with records of rainfall totals and reservoir water level revealed potential connections between recent variations in seasonal rainfall totals and the deposition of sand-size particles in the reservoir.

Potential links between the onset of increased sedimentation in the reservoir cores and trends in rainfall and reservoir level fluctuation are interpreted in two ways. The first is concerned with the potential effects of diverging seasonal rainfall on the catchment sediment transfer system, with low transport capacities during the summer resulting in temporary storage of fluvial sediments. Brief periods of mass sediment transfer will occur during the first few significant rainfall events, when sediment stores are reactivated, resulting in substantial quantities of coarse-grained sediment being delivered to the reservoir during single events. The second interpretation considers the impact of large magnitude increases in reservoir water level over short timescales that are likely to result in flushing of sediment from the proximal delta and reservoir margins downstream towards the dam. This process will be most effective during periods when the reservoir levels are lowest. This interpretation was supported by evidence from air photographs of reworking of sediments in pre-impoundment channels during periods of drought. Based on a conceptual model of sediment deposition in Burnhope Reservoir, deposition of coarse-grained sediment in the proximal and distal sections of the reservoir is dependent on reservoir levels and seasonal rainfall patterns. Although these distinctive connections have been made between recent variations in seasonal rainfall totals, reservoir operations and particle size of sediments, without further analysis of the pathways of sediment transmission through reservoirs, the exact source of these sediments cannot be determined.

9.2 Critique of research methodologies and suggestions for future research

The current study has taken a sediment budget approach to understanding sediment delivery systems in a previously unstudied North Pennine catchment. There are logistical problems related to the various measurement techniques for each component of the sediment budget in relation to the spatial and temporal variations in the processes they measure. A connection has been made between recent variations in seasonal rainfall totals, reservoir operations and particle size of sediments in reservoir storage but the available data from the current study are insufficient to determine the exact sources of these sediments. In evaluating the objectives of this research several key topics deserve further consideration. The main areas of future research can be split into monitoring and modelling of sediment dynamics.

9.2.1 Monitoring

The monitoring of sediment loads from catchment streams in this study was restricted to gauging stations at the inflow to the reservoir. This location was chosen as it provided the most representative estimates of suspended sediment influxes from the main catchments to the reservoir. Further research into the location of sediment sources and the variation in potential sediment supply from first and second order channels would resolve questions about spatial variability in sediment supply in the catchments. By extending the monitoring programme to include gauging stations at confluences of first and second order channels, this would provide a better spatial representation of sediment routing in the catchment. Extending the monitoring programme over two full years would provide data for extending the sediment-rating approach and may resolve some of the uncertainties in the rating relationships.

In terms of further investigation into sediment supply from individual sources in the catchments, photogrammetry could be used to monitor and quantify erosion on stream-side scars, while erosion pins could be inserted to monitor variations in supply from cut banks. The field mapping and analysis of potential sediment sources in the Burnhope and Langtae channels can be extended to incorporate the unsurveyed streams, which would provide a complete catchment scale survey of sources and sinks of sediment. Monitoring of reservoir shoreline erosion provided interesting results relating to the supply of fine sediments and storage of coarse-grained sediments along reservoir margins. Monitoring of bank erosion on an annual timescale would provide further data on variations in seasonal erosion, while installation of sediment traps along the reservoir margins would provide estimates of coarse-grained sediment storage.

There are no published studies that report on direct monitoring of sediment deposition in upland UK reservoirs. Installation of traps on the bottom of the reservoir would enable processes of fine particle deposition to be investigated and would provide valuable information on the spatial transmission of sediment through reservoirs. These data from sediment deposition could be considered along with data from shoreline erosion to better understand the connectivity between supply and deposition within the reservoir sediment budget.

9.2.2 Modelling sediment dynamics

From research carried out at Burnhope Reservoir, the field-based approaches of applying bathymetric surveying, air photograph interpretation and coring techniques have provided valuable information on the spatial and temporal patterns of sediment deposition in the reservoir. However, no data relating to sediment transfer within the reservoir were collected and the connections between sediment supply and deposition has been restricted to conceptual models of sedimentation related to fluctuations in reservoir water level. Modelling of sediment transmission through reservoirs would elucidate processes of sediment re-suspension and re-distribution in shallow shelf areas to deeper sections of the reservoir.

Recent developments in modelling using Data-Based Mechanistic (DBM) and two-dimensional Computation Fluid Dynamics (CFD) modelling has provided an opportunity to bridge the limits of empirical research and elucidate sediment routing to and within reservoirs over longer timescales than currently available from existing monitoring programmes (cf. Price *et al.*, 2000a & b; Rowan *et al.*, 2001; Molino *et al.*, 2001). Numerical modelling using 2D or 3D CFD codes has led to advances in understanding and predicting spatial patterns of flow over floodplains and rivers (e.g. Bates and Lane, 2000) and also has considerable potential as a tool for understanding reservoir sedimentation.

The DBM modelling approach uses time-series techniques that incorporate Transfer Function models to accommodate linear and non-liner dynamic systems (Price *et al.*, 2000a & b). This approach is particularly suited to fluvial systems, as sediment fluxes and stream flow comprise a series of non-linear processes that need to be accounted for in the model (Price *et al.*, 2000a). Preliminary application the DBM models to explore magnitude – frequency relationships and their implication for event horizon preservation within reservoir sediment profiles in Wyresdale Park Reservoir, Lancashire reported encouraging results. Suspended sediment concentrations and discharge at the inflow and outflow of Wyresdale Park Reservoir were averaged to provide daily means than were then compared to daily rainfall records. Long-term daily deposition rates were determined from long-term rainfall records using the DBM model. The application of this model is one of the first examples of modelling coarse-grained layers in reservoir sediments in terms of storm event magnitude and frequency in the UK. Application of the DBM modelling approach to Burnhope Reservoir would require further monitoring of sediment inflows and outflows in terms of particle size and total load over longer timescales, this study has provided valuable primary data on which application of a DBM model could be based.

9.3 Original contributions to knowledge

The objectives of the WARMICE project include obtaining a better understanding of sediment delivery processes and the hydrological functioning of previously ungauged catchments under current conditions; improving sediment yield estimation techniques and assessing potential impacts of land-use and climate change on sediment yields. This thesis has fulfilled these objectives for an upland reservoir catchment in the UK. This study is one of the few that attempts to link sediment sources to reservoir sedimentation via sediment delivery. Sediment yield estimates have been made over a range of timescales using stream monitoring and reservoir sediment reconstruction. Sediment transfer under current conditions has been evaluated on event-based and seasonal timescales, which together with high-resolution contemporary rainfall records has provided an understanding of sediment transfer in a previously ungauged catchment. The potential links between the high-resolution reconstruction of reservoir sediments and long-term rainfall records has provided valuable information on historical sediment transfer and together with evaluation of contemporary data, provides a basis for understanding the likely impacts of future climate change on sediment transfer in upland North Pennine catchments.

The sediment budget framework has incorporated contemporary sediment yields with annual estimates from reservoir sedimentation to assess the contribution of sediment from different sources in the catchment and the reservoir. This research provides the first published data on sediment yields from North Pennine reservoirs and is the first to consider the links between reservoir sedimentation, rainfall and water-level fluctuations in a North Pennine catchment. The importance of shoreline erosion and the storage of eroded sediment along reservoir shorelines has been identified. These findings have implications when estimating catchment sediment yields from reservoir sedimentation. Without consideration of the shoreline sources and stores of sediment, difficulties arise in comparing sediment yield estimates from stream monitoring with those from reservoir sedimentation.

Erosion prediction in ungauged basins is being considered at the 2003 International Association of Hydrological Sciences (IAHS) General Assembly. The objective of this symposium is to review recent developments in a wide range of methods and techniques that can be used to characterise runoff and erosion in ungauged basins. The sediment budget approach is one of the methods that can be used to characterise sediment transfer in ungauged basins and despite being classed as a standard tool, is rarely used in upland catchments. More research is required into sediment transfer in upland catchments in the UK, especially in terms of the impacts on reservoir management. The DETR (2001) report has provided preliminary predictions regarding capacity loss of storage reservoirs in Britain. There is a requirement for more accurate estimates of sediment yields and understanding of sediment dynamics in upland reservoir catchments to enable predictions of future capacity losses to be made in line with potential land-use and climate change.

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APPENDICES

Appendix 1 Rating curve data for Burnhope and Langtae.

Appendix 2 2000-01 rainfall, discharge and suspended sediment concentration data for Burnhope and Langtae.

Appendix 3 Burnhope catchment daily rainfall totals 1936-1998.

Figure 5.1 Geomorphological map of the channel in the Burnhope and Langtae systems

A spatial representation of the potential sources and sinks of sediment at the catchment scale