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River Lune Processes

A study of change in the River Lune catchment and recommendations for flood defence management

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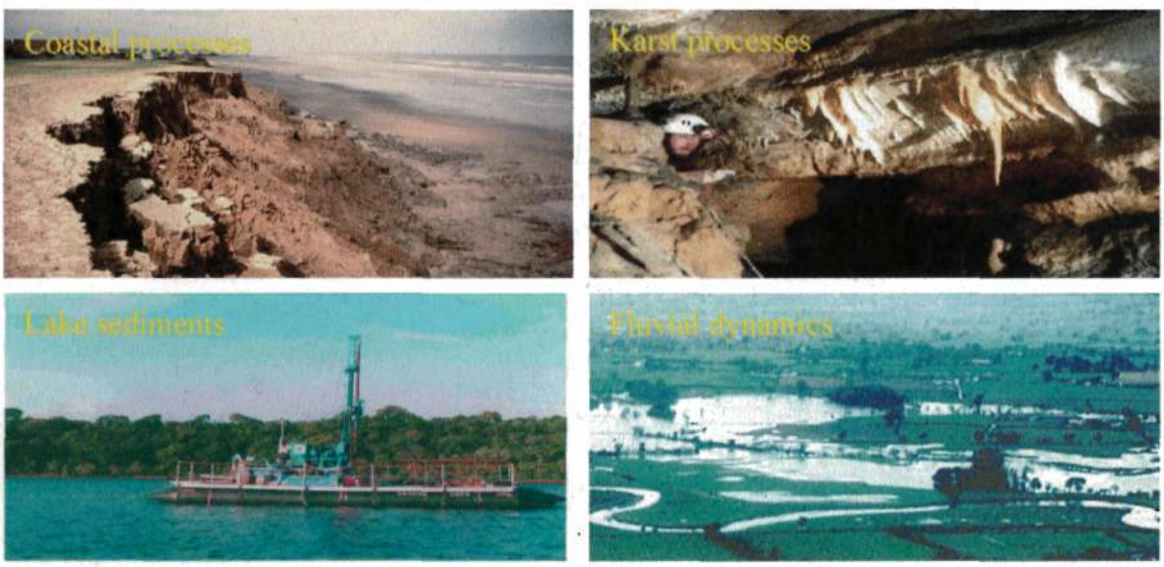

Study of hydrodynamics and sediment in fluvial, coastal and lacustrine environments

EXECUTIVE SUMMARY

Effective forward planning and management of water resources and Environment Agency operations combined with the need to adopt integrated catchment management and sustainable development, requires the thorough understanding of catchment dynamics. Physical processes relating to climate and land use changes are described here for the River Lune. Recommendations are made for long and short-term management of this river.

Increased storminess in the north east Atlantic and the North Sea combined with increased winter rainfall and temperatures have been widely reported for the last few decades. Increased winter rainfall and temperature have also been reported for the Lune catchment during the same time period. If the current trends in the NAO continue these trends are likely to become more exaggerated. Winter rainfall in the Lune catchment has a correlation coefficient of 85% with the annual variability in the NAO.

Rainfall gradients across the UK have become steeper over recent decades related to the strength of westerly (and south westerly) airflows, which increases the effect of orographic enhancement of rainfall, particularly on west facing hills. The result of increased orographic enhancement will lead to greater rainfall intensities, observed in the Lune catchment over the last 25 years. If the current trend in westerly weather continues, the rainfall trends described above are likely to accelerate so that seasonal differences will be greater and wet days will become wetter. The increased winter rainfall is greater and more intense on the upper parts of the Lune catchment than those at lower altitudes.

There is some further evidence of increased variability in rainfall over the last three decades. Distinct cycles have been observed in the rainfall record for the last 100 years that have a frequency of 3.7 years, recently this has increased to 6 years. There is also a cycle in seasonal rainfall trends that occurs every 20 years. These cycles may be related to the NAO and could provide valuable forecasting for rainfall and flooding in the future.

There is substantial qualitative evidence that vegetation in the upper parts of the catchment has changed markedly. The loss of heather and billberry, broom and other similar scrubby vegetation has led to an increase in the area of less nutritious swards particularly bracken and matt grass. These vegetation changes are known to produce reduced interception rates and the subsequent heavy grazing of the resultant grass cover can lead to soil compaction and hence reduced infiltration. All the indicators are that this level of grazing will lead to increased and more rapid runoff.

The upland areas are also more likely to be eroded if the vegetation cover is reduced. Harvey (Pers. Com.) suggests that the Howgill Fells have become relatively stable since the late 1960s in terms of gully erosion, he attributes this to the reduced number of summer storms. The impact of the reported changes in vegetation on fine sediment production are not known, however if runoff is increased it is highly likely that increased amounts of fine sediment are reaching river channels.

There has undoubtedly been a loss of riparian vegetation as a result of grazing pressure leading to active and extensive erosion of river banks at many locations. Past management has involved the removal of riparian trees in some locations. New trees and shrubs are unable to become established; as a result banks are weakened and erode. Channels are becoming wider and shallower in some locations as a result.

Grazing intensity within the Lune catchment has risen dramatically. Evidence from other parts of the UK suggests that the stocking densities from 1988 are high enough to cause erosion and sediment related problems. At present bare soil is visible throughout upland parts of the catchment indicating that the carrying capacity of the land has been exceeded. Farmers may not feel immediate and direct economic effects. However, if this state continues and soil is eroded to the extent that vegetation is unable to recover, the longer term impacts of erosion will be severe (Evans, 1998).

Despite being a rural catchment with approximately 40% (including revetments and severe erosion) of upland the River Lune is perhaps surprisingly heavily managed. Although the previously high levels of channel management in terms of channelisation have been reduced there remains an extensive inheritance of engineered channels. Evidence from other parts of the UK suggests that the extent of field drainage, moor gripping and river channelisation within the Lune catchment is likely to have noticeable impacts on catchment runoff and channel stability.

Flood frequencies have increased in the Lune catchment over the last 50 years. Notable "steps" have occurred in 1950 and 1976. The former is most likely a result of land drainage and channelisation, changes after 1976 appear to reflect trends in increased amounts and intensities of winter rainfall. The contribution of land use activities to the increased flood frequencies between 1976 and the early 1990s is difficult to separate from the climatic variability.

Increased flooding and a greater number of low flow days particularly in summer have produced a more "flashy" regime. The flood regime is likely to have increased the amount of time when stream power is sufficient to cause erosion increasing the risk of bank erosion and fine sediment production.

Runoff within the Lune catchment is spatially variable with reduced runoff in the lower catchment and increased runoff in the upper catchment. There may be greater evaporation and abstraction in the lower catchment whereas runoff in the upper catchment may be responding to greater rainfall intensities and possibly to reduced vegetation cover. There appears to be some change in these trends around 1990.

Seasonal extremes in runoff are most significant in the upper areas of the Lune catchment, those that are most subject to orographic enhancement of rainfall. Seasonal extremes are not significant in the lower catchment e.g. on the River Wenning.

Land drainage activities have produced instability problems in the Lune that the river has been unable to adjust to, despite the instability being moved both up and downstream. Direct channel modifications have resulted in a loss of deposition features; new deposition areas have developed in response that may be giving the impression of increased gravel deposition.

Sediment related problems account for much of the flood defence maintenance and new works activity. Incorrect or, non identification of the cause of sediment deposition has resulted in failed works that have been destroyed by floods or have merely shifted a problem to another location. A majority of bank revetments on the main channel of the Lune have been followed by erosion up or downstream.

Severe erosion of river banks on the Lune in its main floodplain extends to 40% (including revetments and severe erosion); more moderate erosion is evident along much of the remaining banks. Physical habitat in this area is poor and instability is likely to continue unless good vegetation cover protects bare banks. However the cause of erosion problems is not simply related to stock access and overgrazing of river banks.

Field and moor drainage combined with intensive grazing of upland vegetation and intense winter rainfall over the last 25 years have jointly contributed to a change in the flow regime of the River Lune. This threshold change is continuing and a state of dynamic equilibrium has not been reached. Stream power has been increased (by more frequent floods) sufficient to accelerate erosion of banks left vulnerable by grazing animals.

The implications of this study are clear, the catchment and its river channels cannot sustain the current land use activities and is unlikely to withstand the impacts of future climate in its current state.

The Environment Agency has the remit to promote sustainable development and catchment management; potential solutions are presented for the long-term management of the Lune. Recommendations include: establishing a Lune rivers group, restoration of realigned channels, educating riparian landowners as to the benefits of bankside vegetation in controlling erosion and the use of buffer zones and monitoring changes in channel geometry and stability, particularly where fencing or stock restriction is used. In addition the Agency can educate landowners on the benefits of blocking moor drains, explore opportunities for creating wetland areas and other potential water storage areas and encourage the development of floodplain zoning to allow channel migration, potentially using agri-environment schemes.

It is recommended that short-term management options for the control of bank erosion should exclude stock where banks are subject to uncontrolled grazing and allow vegetation to become established. If erosion is severe willow staking could be considered, where vegetation is insufficient to control erosion toe revetments could be used, ideally pinned trees or other natural materials or local stone as a last resort. Bank repairs should be carefully located so that appropriate channel geometry is maintained.

This study fulfils the agency's duty to conduct surveys of the areas in relation to which it carries out flood defence functions. In particular the requirement to complete surveys of the condition and maintenance requirements of all constructed works or assets owned, managed or maintained by the Agency (NRA Flood Defence Strategy, 1993). The same document requires that survey data be used as an input to catchment management plans and performance measures. This project also fulfils the need to support R & D that will assist in identifying future flood defence needs.

PROJECT RELEVANCE

The project examines the 1000km^2 catchment of the River Lune to identify all the factors influencing its physical behaviour. Particular emphasis is placed on flood defence operations with respect to changing climate and land use. The results from this study will be useful for all those involved in strategic planning and sustainable development in this catchment. The report may be used by local flood defence, ecology and fisheries staff to target activities and maximise benefits, in particular areas of the catchment. Tools are provided to assist with decision making in the field. These include a policy-based decision making diagram and maps that characterise particular reaches of the river, highlighting key physical processes and recommendations.

The relevance of this work to other areas of work within the Environment Agency is bulleted below.

- The project is specific to the River Lune but most of the principles and methodologies adopted may be used in other catchment-based studies.

- Results from climate data analysis are likely to be applicable to other north west rivers and may help with future resource planning in the region.

- The effects of land use on runoff response discussed in this report are only likely to be applicable to catchments with similar land use, topography and hydrology. However, the techniques of time series analysis used to examine changes in runoff response are useful tools that can be applied to all rainfall and runoff records.

- The time series modelling methods applied in this study have identified cyclical behaviour in rainfall that may be exploited to aid flood forecasting.

- Geographic Information Systems have been used in this work to provide management tools, highlighting their application to integrated catchment management and sustainable development.

STRUCTURE AND USE OF THIS REPORT

The report presents the findings from a three year PhD study funded by the Environment Agency North West Central Area. The brief was to investigate changes in the River Lune and make recommendations for future flood defence management taking due regard of other environmental or social concerns.

The first section of the report details the background and objectives of the project and introduces the subject areas investigated during the study. Sections 2 to 5 represent the main body of work on this project and serve as the basis on which recommendations are made. These sections give detailed literature reviews, data analysis and results from the investigation. Each of these sections makes summary conclusions including key issues for quick reference.

Section 6 includes all information and recommendations relating to future management of the River Lune. A concise overview of policy and statutory obligations is presented and used to support management recommendations. Recommendations and suggestions for long and short-term management of the catchment are presented. Catchment and channel process maps are provided (in Section 5) to aid decision making, particularly with regard to, the control of erosion, land drainage consent applications and habitat improvements. This section and the tools provided may be used separately from the preceding sections for information if required.

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SECTION 4 CHANGING RIVER REGIME

SECTION 5 GEOMORPHOLOGY AND EROSION

SECTION 6 IMPLICATIONS FOR RIVER AND CATCHMENT MANAGEMENT

SECTION 1 INTRODUCTION

1.0 PROJECT BACKGROUND

There has been a perception of increasing river channel instability in north west rivers and the River Lune in particular in recent decades. This has been attributed variously to: (a) long-term trends in precipitation-runoff regime; (b) changes in land-use such as moor-draining and sub-soil draining such that the river is more flashy than previously, and (c) a change in the magnitude-frequency relationships of flow such that high discharges are occurring with increased frequency.

It has not always been clear whether remedial work in the form of hard engineering or dredging of gravel shoals is the most appropriate measure to manage channel stability. Imposition of hard-structures may merely move a channel-stability problem downstream, whilst the "do-nothing" scenario which may allow the river to find it's own equilibrium has social, economic and policy implications.

Resources are available in the form of rainfall and runoff records, archived information on channel planform, land use statistics and local engineering experience which have not been jointly and fully evaluated. Effective interpretation of the nature of channel change through time with respect to this resource may enhance the Environment Agency's ability to manage the river channel efficiently in the future and will aid the development of effective policy. The results of this study will for the first time, provide robust guidance with respect to long-term channel adjustment and the appropriate management options. The research provides suggestions as to how policy might be developed taking account of other pertinent factors.

1.1 PROJECT OBJECTIVES

The general objective of this project was to assess the effectiveness of river engineering against a background of changes in river hydraulic and sediment regime; specific objectives are listed below.

Special Objectives

1. To determine if there are trends in river bed aggregation/degradation through time.
2. To identify any trends in rainfall-runoff linked to channel change.
3. To determine whether, and to what extent, natural river erosion/accretion should be managed.
4. To determine best practice for channel management including examination of alternative and soft engineering approaches.
5. To identify implications for channel stability of adopting different channel management practice.
6. To identify any other environmental, fisheries or social implications of adopting different channel management practice.
7. To produce recommendations for channel management in EA report form.

1.1 SUBJECT BACKGROUND

In 1991 Newson and Lewin published a paper in response to a policy by government (MAFF, 1990), regarding likely changes in flood defence and erosion protection requirements for England and Wales, following the predicted global warming of the next forty years. Newson and Lewin (1991) were concerned that whilst global climate change modelling had been instrumental in bringing about policy changes on the emission of greenhouse gasses, it is inadequate in the case of river management scenarios because of the complexity of river response. One climate change scenario can produce very different impacts in different catchments depending on both the current climate of the catchment and its physiographic properties (Arnell, 1996). The scale of the drainage basin has become the logical unit for river management and the importance of investigating climate change at this scale has been recognised. Efforts to determine recent climate changes and fluctuations in the UK at the catchment scale have been undertaken by Smith and Bennett (1994).

Effects of climate change are likely to be very subtle especially over timescales of a few decades (i.e. during the period of record for this catchment). The effects of changing landuse may be difficult to separate from climatic variations but this should be possible to examine if observed regime changes in the river cannot be fully explained by precipitation variation. Climate and land use changes and their impacts are particularly important for developing integrated catchment management. The issues raised by the contemporary 'climate debate' have helped to highlight sustainable development whereby rivers are used in such a way as to maintain them as a resource for the future. In order to achieve integrated catchment management, and sustainable development, it is essential to have a thorough understanding of the system dynamics and to account for climate changes in the future.

Catchments are defined by the topography of the surrounding land, in Britain landforms are the result of glacial, periglacial and fluvial activity. The hydrology and sediment characteristics of a river catchment are thus the result of landform development, climate and land use. Geomorphology has most frequently been defined as the study of landforms; fluvial geomorphology examines the forms created specifically by river systems.

Gregory (1977) in his introduction to "River Channel Changes" describes the historical development of fluvial geomorphology as consisting of two schools. The "empirical" school sought to understand rivers through observation (e.g. Leopold *et al*, 1964; Blench, 1957; Schumm, 1968) providing important descriptive generalisations, particularly at larger scales. The "fundamentalist" school worked with mathematical models based on physical principles and aided by laboratory studies (e.g. Kondrat'yev, 1969; Bridge, 1975); this approach led to valuable insights into mechanisms but incorporated considerable oversimplification and, until recently, has been limited to small scales. Gregory (1977) concluded that future work should include quantitative studies of responses to river processes with measurements made at spatial and temporal scales appropriate to these processes. Gregory (1977) identified the principal research need as being the transfer of sediment in relation to spatially and temporally varying flow. The last two decades have seen a proliferation of small catchment studies and measurements of sediment transport (e.g. Harvey, 1979 and 1991; Carling, 1983) and the development of a whole new field of research:

turbulence and coherent flow structures (see Clifford *et al*, 1993). The increasing threat of global climate change and anthropogenic influences on the landscape and particularly rivers has fuelled research into process response.

Advances in measurement techniques and an increased understanding of some process mechanics (e.g. secondary flows, turbulence, and bank erosion), has led to new frameworks for the analysis of rivers. Concepts range from the streamway concept to the river continuum theory (Vannote, *et al*, 1980) and other models of connectivity between the channel and the floodplain. These approaches have incorporated new research output and directed it towards applied river management (e.g. Thorne *et al*, 1997). Traditionally river management has been the domain of many separate disciplines because of the complexity of river systems. Fluvial geomorphologists have sought to make the science more accessible and to highlight the importance of physical processes and in particular the risks of ignoring physical processes. Although in most cases the knowledge base is inadequate to predict the timing and location of precise changes in river systems, the potential impacts of any change to the river can be identified.

The discipline of fluvial geomorphology has grown from geography and hence has inherited a concern with dimensions of scale whether temporal or spatial. Scaling factors in river catchments are highly complex, from the temporal delays between rainfall and runoff, to the spatial extent of channel erosion. Unravelling time lags, and spatial effects of activities in different areas of a river catchment, are critical for an understanding of the processes in operation. Beginning to understand the active processes in large catchments, such as the River Lune, that are made up of distinctly separate sub-catchments, requires a knowledge of past and present climate, geology, soil type, topography, land use and hydrology.

This study investigates four key areas in detail. Climatic variability is used as a framework for the analysis of rainfall trends within the Lune catchment and the northwest of England. Subtle trends in the data are extracted using sophisticated time series analysis. Land use is examined over a range of timescales; emphasis is placed on recent grazing intensities and land drainage practices. Changes in the discharge regime and spatially variable runoff response are presented for the period of gauged record. Trends in flood frequency are identified and some assessment of flood generating mechanisms is made. Historical maps and aerial photographs together with field evidence are used to characterise the fluvial geomorphology of the River Lune. The historic and contemporary distribution of erosion is analysed using Geographic Information Systems.

SECTION 2 CLIMATIC VARIABILITY

2.0 INTRODUCTION AND OBJECTIVES

River flows may be changing as a result of fluctuations in climate or as a result of anthropogenic disturbances, or a combination of these two. Regardless of human influence, long and short-term trends in climatic variability are important for water resource planning and management.

The last three decades have been described as the most climatically variable in recent times. During this period seasonal rainfall patterns have become more extreme and rainfall intensities have increased in the Lune catchment. Examination of trends in large-scale climatic indicators and trends in local temperature, suggest that these trends will, in all probability, continue in the future. Sophisticated statistical methods of time series analysis, have been used to extract subtle trends in rainfall. Regular cycles in the rainfall pattern have been observed which may provide a tool for future predication of rainfall amounts and seasonality.

The Inter-Governmental Panel on Climate Change (IPCC), reporting in 1995, concluded that climate has changed over the last one hundred years. Global mean air temperatures have increased between about 0.3 and 0.6 °C since the late 19^{th} century. Recent years have been among the warmest since 1860 (in the period of instrumented record). On regional scales there is clear evidence of changes in some extremes and climatic variability indicators, but data are inadequate to show whether these changes are consistent on a global scale (Houghton *et al*, 1996).

In an attempt to understand the relevant processes operating with respect to the Atlantic Ocean, Marshall and Kushnir (1997) drafted a paper to guide future work. They report that the countries surrounding the Atlantic basin have, in the last fifty years or so, experienced dramatic changes in climatic conditions. Since the 1960s there has been a steady increase in wintertime storminess in the northeastern Atlantic and the North Sea. At the same time northern European countries bordering the Atlantic have experienced an upward trend in winter rainfall. Winter air temperatures over northern Europe rose steadily from the 1960s. There is some evidence to suggest that these trends may be reversing in the late 1990s heightening concern about the future. The mechanisms that drive change around the Atlantic are not well understood but it is felt likely that the answers may lie in an examination of the North Atlantic Oscillation (NAO).

At the local scale, and in the short term, climatic fluctuations that influence rainfall distribution and intensity over a year have immediate implications for water resources. It is important to assess short-term variability in the light of long-term trends in order that planning can be undertaken for the future. It is also important to know if the variability observed over the recent past is likely to continue.

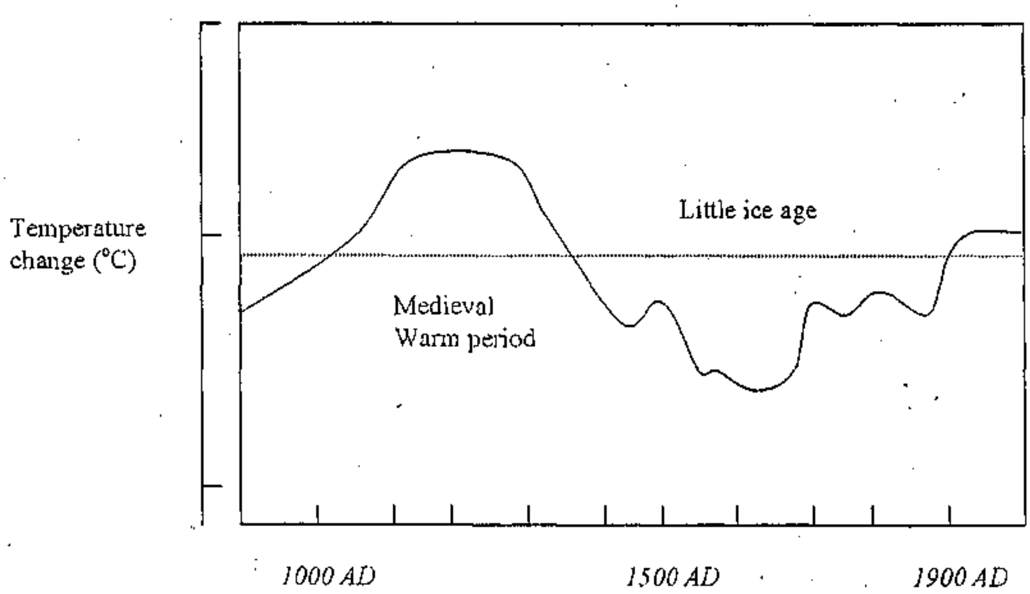
Global, national and regional trends in rainfall distribution will be examined, such that changes in the Lune catchment can be placed in a regional context. Rainfall variability in the northwest of England will be compared with appropriate climatic drivers. Correlations will be made between annual and seasonal variability in rainfall, weather types, the North Atlantic Oscillation Index (NAO) and position of the Gulf Stream. The NAO Index is believed to be a significant arbiter of rainfall patterns in northern Europe, whilst the position of the Gulf Stream has been linked to biomass and vegetation growth in Britain. The relative importance of long term trends (climate change) and short-term fluctuations (climatic variability) in rainfall will be considered in relation to these climatic drivers.

Long-term global and regional temperature trends influence large-scale circulation systems and vice a versa; large-scale circulation systems can be examined through relevant indices pertaining to the NAO and the Gulf Stream. Local temperature variability will be compared with national trends since temperature has an impact on evapotranspiration, which in turn affects the amount of runoff. The separation of climatic effects from anthropogenic influences on river flow and changing flood-generating mechanisms will be addressed in Chapter 4.

2.1 CLIMATE VARIABILITY – PATTERNS AND PROCESSES

By convention and tradition, climate is usually represented by thirty-year averages. The term 'climatic change' is usually reserved for variations of at least thirty years duration (Mayes and Wheeler, 1997). However the analysis of averages may mask trends in extremes of climate which may have important environmental, social and economic effects. Mayes and Wheeler (1997) cite the example of the number of frost days, a small variation in which may have very significant agricultural impacts. It is also important to refer to climate change within the context of long time scales of climatic fluctuations. Current temperatures can be seen in context in Figure 2.1 redrawn from Folland *et al* (1990) for the last 1000 years including the Medieval Warm Period and the Little Ice Age. The characteristics of weather and climate at

Figure 2.1 Global temperature, the last 1000 years (after Folland et al, 1990)

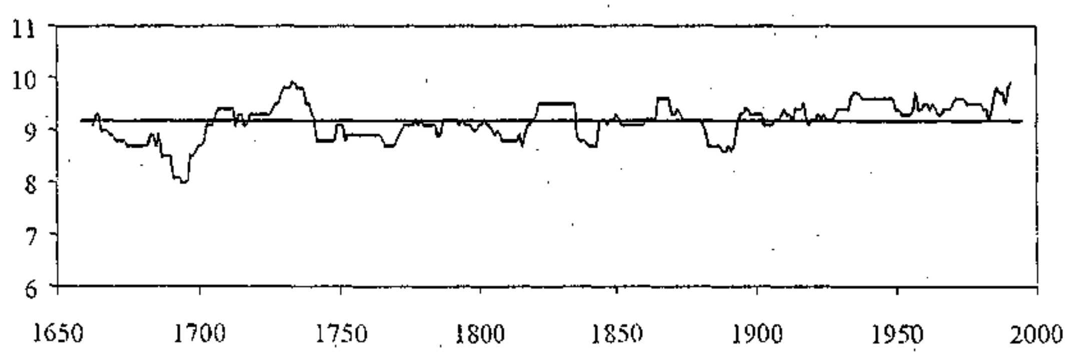


these times are summarised by Mayes and Wheeler (1997) and will not be discussed further. It should be noted that the close of the little Ice Age is difficult to date precisely, but it most certainly extended into the eighteenth century and even in the late nineteenth century there were a number of very cold winters. It was described previously that the long-term climatic changes (hundreds of years) are measured by examination of mean values. For change to occur climatic indicators (e.g. rainfall and temperature) must change about a mean value in the short-term (10 to 100 years). The earliest indication of climate change is increased variability. Variability may be detected in the short-term by changes in total annual rainfall and less obviously, by changes in the distribution of rainfall over the hydrological year. Short-term variability may also be detected in rainfall by changes in intensity, which are not apparent from examination of total rainfall statistics. These, often subtle, changes have immediate impacts on river catchments and pose challenges for river managers. Increased winter rainfall is likely to lead to increased flooding and more frequent drought conditions in summer, the latter during times of peak water demand. A more extreme rainfall regime affects river runoff with inherent issues for flood defence, water resources and ecological systems, particularly for migratory fish. These effects will be better defined in responsive catchments such as the river Lune.

2.1.1 Temperature and evapotranspiration

Global mean temperatures have increased between 0.3 and 0.6 °C since the late nineteenth century. The long-term trend in temperature was shown in Figure 2.1; the central England temperature (CET) from 1750 is shown in Figure 2.2. This data set was compiled by the late Gordon Manley and can be acquired from the Climatic Research Unit (see also Hulme and Barrow, 1997). The trend (five year median filter) is upwards for the whole period and consistently above the mean value from 1900 onwards. The same trend can be observed in the central Lancashire data series derived from amalgamated records in north west England (Manley, 1946 and 1976). Data from 1970 onwards is from Hazelrigg Station at Lancaster University, see Figure 2.3. The seasonal trends in temperature variability are also worth noting (see Figure 2.4).

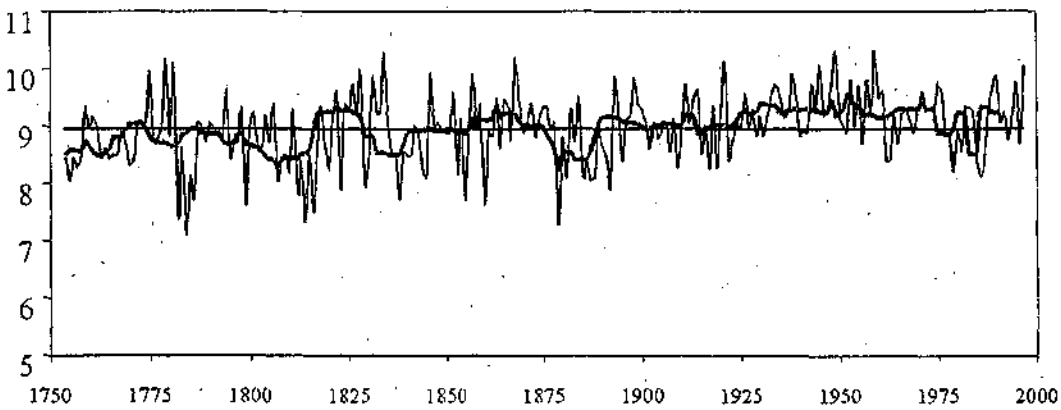
Figure 2.2 Mean annual CET (°C)



Winter mean temperatures are consistently above the mean between 1970 and 1998; the same trend is not present for summer temperatures which have been below the mean for the same period.

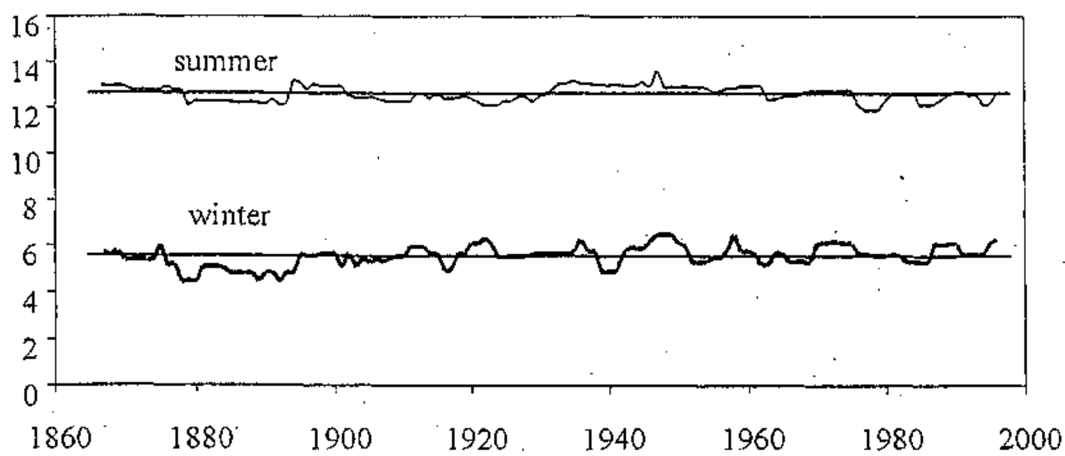
It is likely that increased global temperatures will lead to an increase in potential evapotranspiration. Evapotranspiration is the sum of water used by vegetation in transpiration and in evaporation from soil surfaces, or intercepted precipitation in an area at any given time. Evapotranspiration represents the main consumptive loss of water from the hydrological cycle; Hudson *et al* (1997) estimate that 15-20% of rainfall in the British uplands is lost by transpiration from grassland, 30-49% is lost from areas with full forest cover. Evapotranspiration is most commonly expressed as potential evapotranspiration (PET), which assumes an unrestricted supply of water and can be estimated from semi-empirical formulae (Penman, 1948). Actual evapotranspiration is the actual or observed loss, if conditions of optimum water supply exist· this can exceed PET. It has been suggested that a 1°C increase in temperature will lead to a 5% increase in PET (Raper *et al*, 1997). However changes in relative humidity could lead to an actual decrease in PET, this has been suggested as a likely outcome in the north and west of Scotland. The sensitivity of PET changes as a result of increased temperatures is not well understood for much of Britain.

Figure 2.3 Mean annual Lancashire temperature (°C)



Penman's formula indicates values for PET from 400 mm pa in Scotland to about 510 mm pa in southern England (Penman, 1950). PET is usually derived from average values of temperature, vapour pressure, wind speed and global radiation, with temperature and relative humidity being the most influential.

Figure 2.4 Mean seasonal temperature Lancashire (°C)

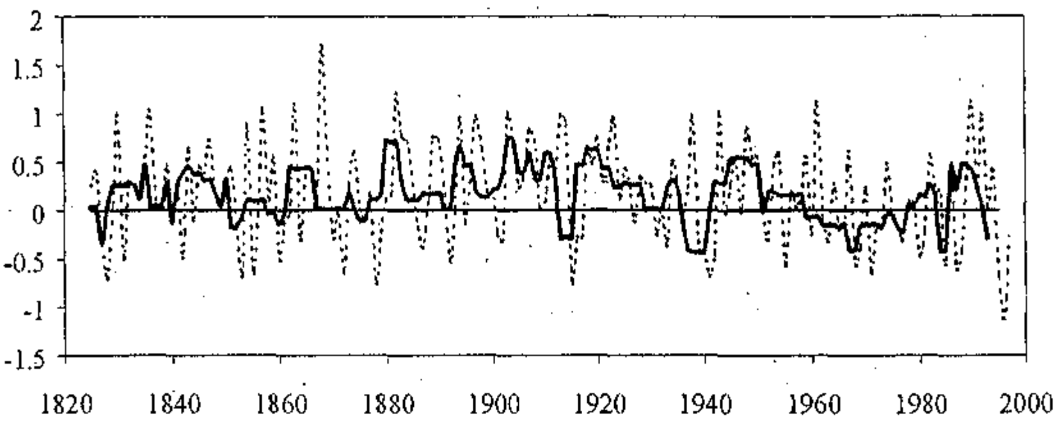


2.1.2 The North Atlantic Oscillation

The prevailing airflow types over Britain are determined by large-scale circulation systems that in turn may be influenced by fluctuations in global temperatures. While the precise mechanisms are not known in detail, the equator to pole temperature gradient appears to control the strength, pattern and position of circumpolar flow (Lamb, 1982). The pattern of surface pressure over the Atlantic is dominated by the Icelandic Low and the Azores High. The North Atlantic Oscillation Index (NAO) (Davies *et al*, 1997) is a measure of the gradient of sea level pressure between these two. High values of the NAO Index are strongly zonal and are associated with increased westerlies across north west Europe (Wilby *et al*, 1997). Circumpolar upper airwaves in the northern hemisphere tend to alternate between two specific forms, zonal and meridional (Hirschboeck, 1988;Knox, 1984; Lamb, 1977; Charney and DeVore, 1979). Under warmer conditions in the middle and lower latitudes of the northern hemisphere, flow is strongly zonal (west to east) with low amplitude, widely spaced waves. During cool episodes, the longitudinal temperature gradient is steepened, favouring more frequent and enhanced occurrences of large scale meridional (north/south) wind patterns in the upper atmospheric westerly circulation. When the flow is meridional the development and passage of the cyclonic waves is 'blocked'. Blocking occurs most commonly in spring and early summer in Britain (Davies *et al*, 1997). Occasionally, the NAO Index is negative so that the pressure gradient is reversed; this extreme circulation mode reflects a strong pattern of blocking and results in an easterly air flow over northern Europe. Such patterns can persist for a whole season for example the winter of 1963, one of the coldest in the last 250 years in Britain was associated with very low values of the NAO Index (Davies *et al*, 1997).

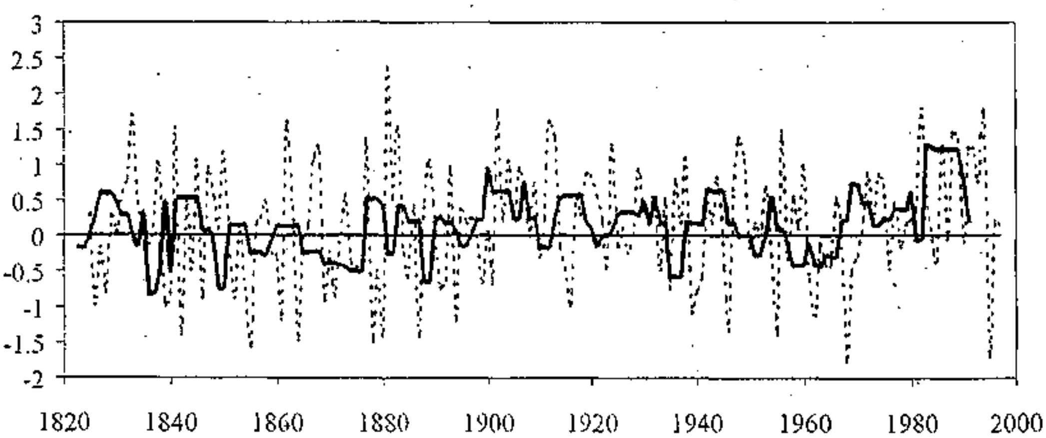
Meteorological observations have allowed the timing of changes between meridional and zonal upper atmospheric circulation configurations to be established for the last 100 years or so, with major break points identified around 1895, 1920 and 1950 (e.g. Dzerdzeevskii, 1968; El-Kadi and Smithson, 1992; Kalinicky, 1987; Knox *et al.*, 1975). It has been suggested that short term fluctuations in upper atmosphere circulation patterns may be a possible causal mechanism for high-frequency hydroclimatic changes (Knox, 1984; Rumsby and Macklin, 1994). The variability in the annual value for the NAO Index is shown in Figure 2.5. The index is defined as the normalised pressure difference between a station on the Azores and one on Iceland. The data can be obtained from the Climatic Research Unit at the University of East Anglia or from their website (http//www.cru.uea.ac.uk/cru/data/nao.htm). The annual series shows an upward trend from the 1960s and considerable year to year variability.

Figure 2.5 Annual NAO Index showing 5yr median filter trend



The NAO Index is strongly correlated with westerly days over the British Isles, the correlation ranging from 0.75 in winter to 0.43 in summer (Jones and Hulme, 1997). It seems therefore that the annual index of NAO is a good indicator of winter weather conditions; winter time series are shown in figure 2.6. Low values of the NAO Index in winter during the period 1900 to 1930 were followed by a downward trend between 1940 and 1970. A sharp reversal in the trend has been observed in the last 25 years with unprecedented high values since 1980. The last two years have seen a reversal of this trend. Decadal variation in the NAO Index since 1950 has been especially pronounced, the causes are not clear but the impact of greenhouse gas forcing and possible links to coherent variations in tropical Atlantic sea surface temperature anomalies may be important (Hurrel, 1995). If the trend in the NAO continues then we can expect that a greater percentage of rainfall will fall in winter. The winter series

Figure 2.6 NAO Winter Index (ONDJFM)



shown here is for the period October through to March to coincide with rainfall data presented later in this section.

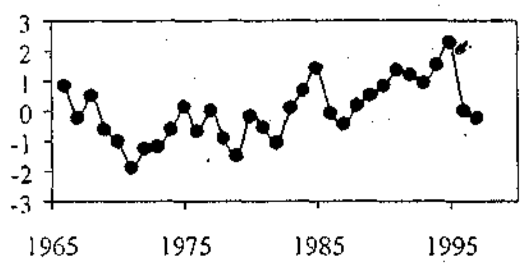
2.1.3 Position of the Gulf Stream

The Gulf Stream is a warm ocean current that originates in the Gulf of Mexico, high temperatures around the equator heat the oceanic water and the Earth's rotation forces this warm water to move. It flows first north along North America, then turns east across the Atlantic Ocean. As it approaches Europe, the Gulf Stream turns into what is called the North Atlantic Drift current. From latitudes approximately 30° to 60° N, an area that includes most of North America, Europe and much of Asia, Earth's prevailing winds blow from west to east. As the winds move across the warm North Atlantic Drift and onto the coast of Ireland and Scotland, the air is warmed. The climate of the British Isles and continental Europe is considerably moderated by the influence of the warm water transported by the Gulf Stream. The Gulf Stream, like other western boundary currents, is characteristically very strong, quite narrow, and transports large amounts of water thereby exerting a considerable influence on the dynamics of the entire ocean basin and the regional climate. Two warm equatorial currents merge with water from the Gulf of Mexico to form the Gulf Stream. Off the coast of Florida the Gulf Stream has a maximum width of about 80 km. Farther north the stream increases to approximately 480 km wide off New York. South of the Grand Banks, the stream meets and mixes with the cold Labrador Current and moves northeast across the ocean. The drift then splits into several branches that reach Europe, Iceland, the Azores, and the Canary Islands.

It has long been understood that the position of the Gulf Stream influences plankton biomass within the Atlantic (Taylor and Stephens, 1980), recently it has been related to lake plankton (George and Taylor, 1995) and terrestrial vegetation productivity (Willis *et al*, 1995) in the British Isles. The mechanism is thought to be primarily the effect of the Gulf Stream on early summer warming, thereby influencing the growing season.

It has been shown over the last three decades that the lateral position of the Gulf Stream is closely correlated with the NAO; high values of the NAO Index correspond to more northerly positions of the Gulf Stream about two years later (Taylor and Stephens, 1998). This time delay is likely to be associated with the adjustment time of this part of the Atlantic Ocean circulation. Charts published by a variety of U.S. oceanographic organisations of the north wall of the Gulf Stream, derived from aircraft, satellite and surface observations have been used to define variability in the Gulf Stream position. The latitude of the north wall was determined at six longitudes and principal component analysis used to find the common pattern of variation, the resulting time series from 1966 to 1997 is available from Dr A. H. Taylor at The Plymouth Marine Laboratory or from their website (http://www1.npm.ac.uk/pml). The annual mean position for the north wall is shown in Figure 2.7. The trend in the position of the Gulf Stream has been northwards from about 1970. Principal component analysis has been used to calculate weighted averages of monthly mean sea-level pressure and of monthly mean numbers of cyclone tracks in order to examine changes in weather patterns associated with displacements of the north wall (Taylor, 1996). Zooplankton evidence over the last twenty five years reveal a pronounced atmospheric connection between the position of the north wall and the climate of the European continental shelf. Correlations between mean sea level atmospheric pressure and changes in the number of cyclones accompanying northwards shifts in the Gulf Stream are too small to be significant for local biological communities (Taylor, 1996). It is likely therefore that zooplankton changes have been driven by quite small changes in weather patterns or that the frequency, duration and intensity of cyclones and anticyclones are important.

Figure 2.7 Position of the north wall of the Gulf Stream



The persistence of periods of a particular weather type has been examined over the European mainland in relation to changes in rainfall and flood frequencies. Bardossy (1998) found that, for the generation of rainfall, the duration of a particular weather type was more significant than the frequency with which it occurred. The time series were investigated using a window technique and a serial correlation-type approach, changes in weather type duration were found to be significant.

2.2 CLASSIFYING BRITISH WEATHER TYPES

The tendency for certain weather types to recur with reasonable regularity around the same date is termed a singularity (Barry and Chorley, 1982). Lamb (1950 and 1972) compiled calendars of singularity for the British Isles by studying singularities of circulation pattern. Lamb's weather catalogue is the most widely used synoptic classification for the British Isles and is considered to be the definitive classification (Kelly *et al*, 1997), providing a daily record of dominant weather types for Britain from 1861 to 1995.

2.2.1 Lamb's system

The classification of daily atmospheric circulation according to Lamb's weather systems is largely a subjective approach for an area between 50-60^{o}N and 10^{o}W - 2^{o}E. The method seeks to represent the general flow of the surface winds over the British Isles, rather than the details of the surface winds on a given day (Lamb, 1972). There are eight directional types: north (N), northwesterly (NW), northeasterly (NE), easterly (E), southeasterly (SE), southerly (S), southwesterly (SW) and westerly (W). There are also three non-directional types: anticyclonic (A), cyclonic (C) or unclassified (U). Both directional and non-directional airflow types can be combined to categorise more complex circulation patterns. Lamb (1972) considered seven basic types to be fundamental and these are described in Table 2.1.

Table 2.1 The seven basic weather types, after Lamb (1972)

Anticyclonic (A)	Anticyclones centred over, near, or extending over the British Isles.

Cyclonic (C)	Depressions passing frequently or stagnating over the British Isles. The central isobar of the depression should extend over the mainland of Britain or Ireland.
Westerly (W)	High pressure to the south and low pressure to the north, giving a sequence of depressions travelling eastwards across the Atlantic. This is the main, progressive zonal type.
Northwesterly (NW)	Azores anticyclone displaced northeast or north towards the British Isles. Depressions forming near Iceland and travelling south east into the North Sea.
Northerly (N)	High pressure to the west or northwest of Britain extending from Greenland southwards, possibly as far as the Azores. Depressions travel southwards from the Norwegian Sea.
Easterly (E)	Anticyclones over Scandinavia extending towards Iceland across the Norwegian Sea. Depressions generally to the south of the region over south-west Europe and the western Atlantic.
Southerly (S)	High pressure over central and northern Europe. Depressions blocked to the west or travelling north or northeastwards off western coasts.

2.2.2 Critique

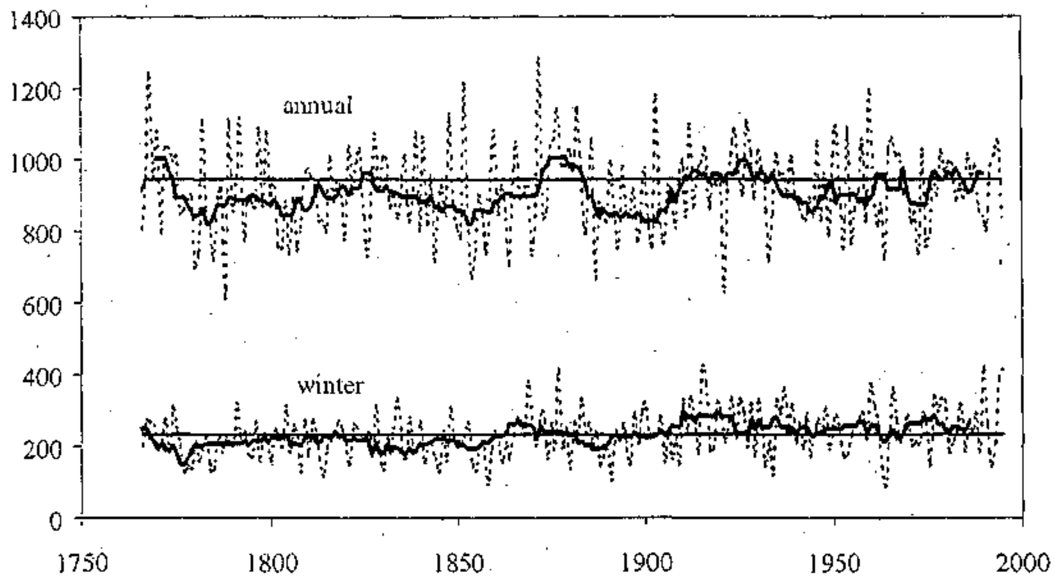
There are limitations associated with Lamb's classification system, in particular its inability to distinguish between different regions of the British Isles (Mayes, 1991). El-Kadi and Smithson (1992) discuss the subjectivity of Lamb's classification and the disappointing results obtained in temperature and rainfall forecasting and review alternatives to the Lamb classification. Future classifications are likely to be more objective (El-Kadi and Smithson, 1992; Jones *et al*, 1993) in the meantime however the Lamb classification provides a long-term record which has proved its worth in many situations (Kelly *et al*, 1997).

The Lamb classification contains a mass of information; as a result indices are often used to portray major variability. Indices have been defined to describe the degree of progression (mobile, westerly patterns), southerliness, cyclonicity and meridionality (Murray and Lewis, 1966) and frequently used is a simple index of westerliness to monitor the changing strength of zonal flow described above (Kelly *et al*, 1997).

2.3 NATIONAL AND REGIONAL RAINFALL PATTERNS

The duration, intensity, distribution and type (rain or snow) of precipitation over an area are determined by its geographical location (particularly in relation to orographic features) and by characteristics (moisture, content and trajectory) of prevailing airflow types (Gregory *et al.*, 1991). The geography of rainfall in Britain is dictated largely by orographic effects; the north and west parts being the wettest. Mountainous areas of Wales, the Lake District and north west Scotland may have average rainfall exceeding 2000 mm. The Tees – Exe line typically receiving 1000 – 1600 mm of rain depending on altitude, east of this line annual precipitation declines to 600 mm in the south east. An area average dataset has been compiled for England and Wales (EWP) available in Hulme and Barrow (1997) or from Dr Phil Jones of the Climatic Research Unit (see Figure 2.8). The series is compiled from records in five regions of England and

Figure 2.8 EWP (mm) afterJones & Hulme (1997)
(showing 10 yr median filter trends)



Wales, including the northwest. Figure 2.8 shows considerable variation in annual EWP, there is a tendency for wetter winters from 1860. Summer EWP shows a slight decline in total over the last 100 years (Jones *et al*, 1997). Time series of areal average precipitation for Scotland over the same duration show marked increases in total annual rainfall since 1970 reflected in winter, spring and autumn; summer totals have been declining since 1860 (Jones *et al*, 1997). It is expected that data from the Lune catchment may have more in common with the areal average for Scotland because the EWP series contribution from the north west is from stations at Kendal (altitude 91m) in southern Cumbria and Stoneyhurst (115m) in southern Lancashire (Wigley *et al*, 1984). It is generally the case that maximum annual rainfall in Britain for the last 150 years occurred around 1921-30 (Gregory, 1956).

It has previously been discussed that subtle variations in rainfall may be identified by changes in duration and intensity of rainfall events. In section 2.1.3 it was mentioned that the period since 1960 was characterised by an increase in storm activity over the eastern side of the Atlantic. Event rain gauge networks have been established throughout Britain particularly since the early 1990s, previously the majority of gauges provided daily records. As a result the temporal trends for rainfall intensity in Britain are not reported. However it is possible to derive surrogate indicators of rainfall intensity by using thresholds such as the number of days with greater than 15 mm of rainfall in total. Such analysis for seasonal half years has been conducted in Australia (Suppiah and Hennessy, 1998) where periods of increased rainfall intensity have been associated with the Southern Oscillation (Suppiah and Hennessy, 1996).

It has been noted that the NW/SE rainfall gradient across the British Isles appears to have been increasing since the 1970s (Mayes, 1995; Marsh and Sanderson, 1997); the W/E gradient in Scotland has also steepened (Foster *et al*, 1997). In the late 1990s the rainshadow effect of the Pennines was intensified and the seasonal variability in NE

England climate considered exceptional (Marsh and Sanderson, 1997). The fact that the majority of Britain's population lives in the south and east and most of the rainfall falls in the north and west has always posed problems for water supply. Coupled with increasing water demand, changing rainfall patterns are likely to intensify these issues. It is also likely that steeper rainfall gradients will be exaggerated in areas subject to orographic enhancement.

2.3.1 National correlations with weather types

Many studies have attempted to link observed variations in precipitation values with the frequency of weather types. An increase in average annual rainfall of 5-10% over western Britain during the period 1916-1950, compared with 1881-1915, has been attributed to the increase in westerlies during the 1920s and 1930s (Glasspoole, 1954). Since then there has been a decline in the frequency of westerlies over the UK, especially during winter, which has been in part compensated for by the increase in cyclonic and anticyclonic airflows (Briffa *et al.*, 1990). However it has been suggested that a new phase of more frequent westerlies has commenced that is particularly noticeable in Scotland (Mayes, 1991). Mayes (1991) analysis identifies an association between the location of the most frequent westerlies and the largest west – east contrast in rainfall anomalies. He suggests that a local increase in westerlies strengthens the effects of orographic enhancement of rainfall in the exposed west and rainshadow conditions in the more sheltered eastern districts. This supports the earlier work of Gregory (1956) and the later observations of Marsh and Sanderson (1997). For the period 1900-59 in northern England, Mayes (1991) observed a contrast arising between those areas of rapid orographic uplift of prevailing westerly air masses and juxtaposed areas on the eastern, lee side. The former shared a significantly large increase in rainfall amounting to 15% in the Manchester lowland and the Lake District and 10% over Rossendale, The Bowland Fells and the head of the Lune Valley. Actual decreases occurred on the lee of the Pennines and in the Eden valley.

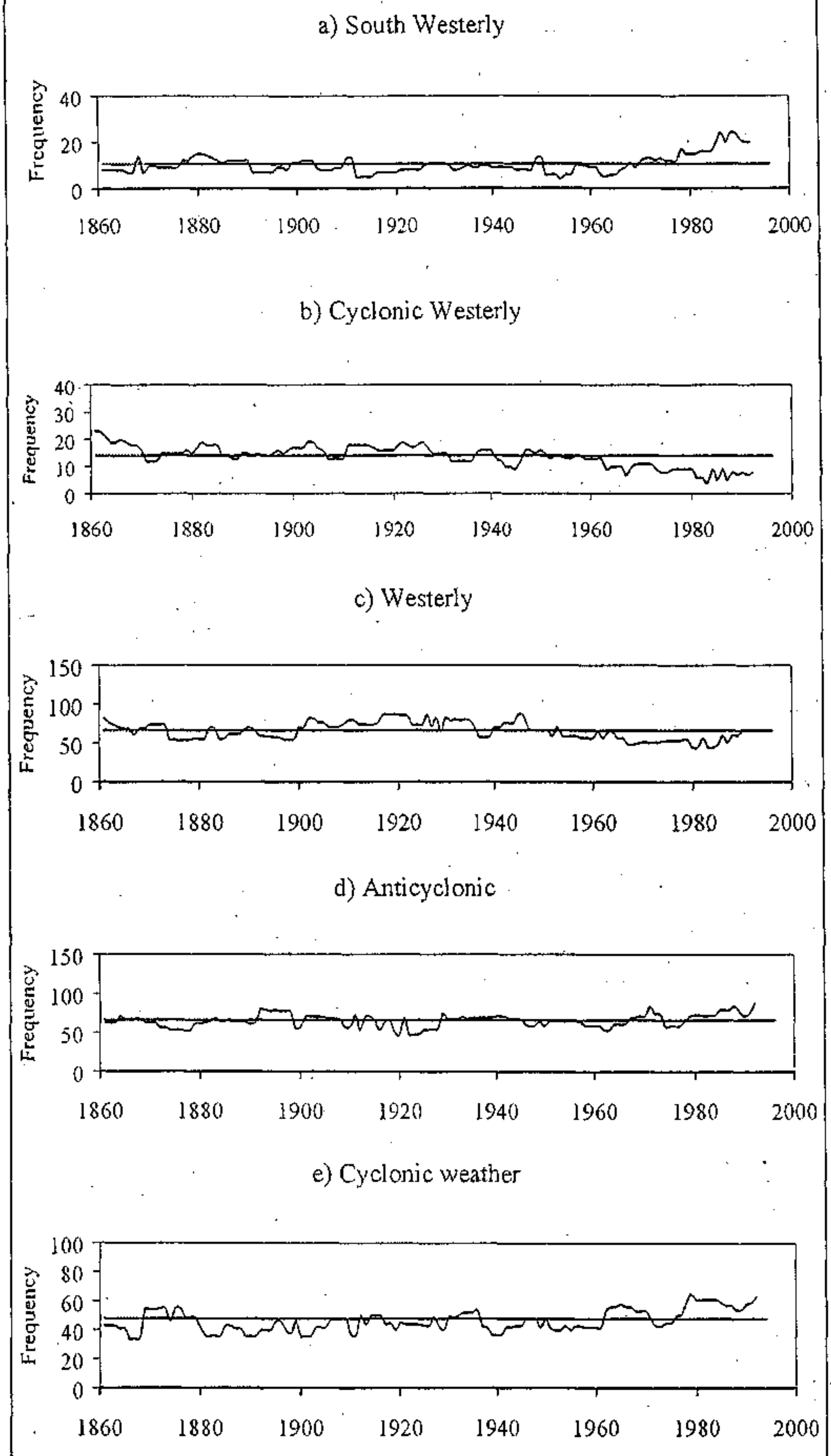
Smith (1995) and Foster *et al* (1997) have observed a strong positive correlation between westerly weather types and precipitation in Scotland. This was particular true for winter periods between 1869 and 1992. Between 1963 and 1992 westerly types showed increased seasonal variation and anticyclonic weather types were less strongly negatively correlated with precipitation (Smith, 1995). This ties in with Mayes (1991) who commented that the most notable change in regional airflow frequency was the increase in westerly activity over Scotland from the mid 1970s. Significant (5% level) correlation coefficients have also been observed between cyclonic and anticyclonic (negative and positive respectively) weather types and the long term England and Wales precipitation series for all four seasons of the year (Jones *et al*, 1993).

Considerable analysis has been undertaken on the geographic variation in rainfall and the prevailing circulation types (Sweeny and O'Hare, 1992). The most prolific precipitation producing synoptic weather type for the British Isles was found to be cyclonic southwesterly. The driest periods coincided with anticyclonic northerly and northeasterly.

2.3.2 Trends in weather types

Time series of the Lamb weather types for the period 1861 to 1994 are shown in Figure 2.9 for the five pure weather types felt to be significant for flood generation in the north and west of Britain. Increased variability in all five weather types is

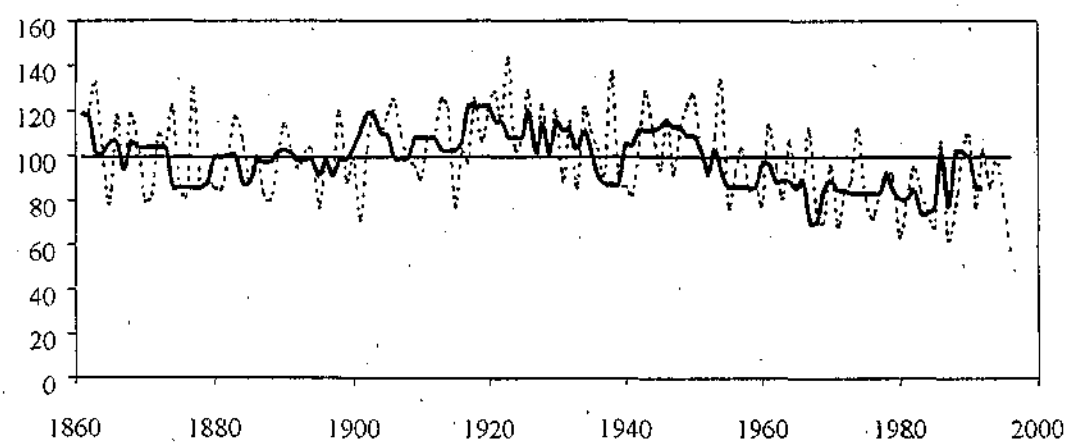
Figure 2.9 Lamb's pure weather types 1860 to 1995



apparent from 1970 onwards. It has been noted by Sweeny and O'Hare (1992) that a significant change in the makeup of the synoptic record has occurred in recent decades, reduced westerly and increased anticyclonic and cyclonic airflows are suggested as being primarily responsible for recent changes in precipitation geography in the British Isles. The rapid increase in the frequency of southwesterly weather types is particularly noteworthy for flood generation in the Lune catchment; this will be discussed in chapter 4.

The weather types shown in figure 2.9 are pure weather types; it is useful to examine the weather types as hybrids using indices. The degree of westerliness has been defined to include all those days which have a fraction of either: westerly, southwesterly, northwesterly or cyclonic westerly. For example northwesterly days are given a value of 0.5 and westerly days a value of 1. The variability in the westerly index is shown in figure 2.10, the seasonal westerly index is shown in Figure 2.11. The frequency of westerly weather during the summer has been declining since about 1950. The lowest frequency of westerlies was observed around 1970 since when it has shown a partial increase although frequencies are still lower than those observed between 1900 and 1950. The rapid increase in Scottish rainfall since 1970, reported in section 3.2, does not coincide exactly with the observed turning point in the westerly index according to Lamb's classification. Mayes (1995) suggested that this could be explained by the mid-latitude westerlies migrating northwards in response to warming. If the zone moved north, the corresponding airflow type over the British Isles as a whole (as recorded by Lamb) might be classified as anticyclonic. This would imply that the frequency of westerlies observed at any one location may not indicate the full magnitude of the general band of westerlies.

Figure 2.10 Westerly index, annual series



If westerly circulation continues to increase the effect will be to modify the broad scale changes in seasonal and geographic rainfall distribution previously discussed, according to local topography. This would give the possibility of increased rainfall on west facing hills and strengthen the magnitude of the rainshadow effect, this is likely to accentuate any tendency for runoff reductions to be concentrated in the south east (Mayes, 1995). Local topographic influences will therefore complicate attempts to define regional runoff trends. It is interesting that Rowntree *et al* (1993), reporting on model predictions from the Hadley Centre Transient Response Experiment, show increasing winter rainfall over northern Europe. They also reported that increased westerly winds would be likely to concentrate rainfall west of high ground, with smaller increases or even decreases to the leeward side. Rowntree *et al* (1993) also suggested that the wettest days were likely to become wetter. The ratio of the frequency of southerly days to northerly days (Lamb's definition) is shown in Figure 2.12, southerly days have been increasing relative to northerly since 1960 and the ratio has remained above average for the longest prolonged period since 1860.

Figure 2.11 Seasonal westerly index

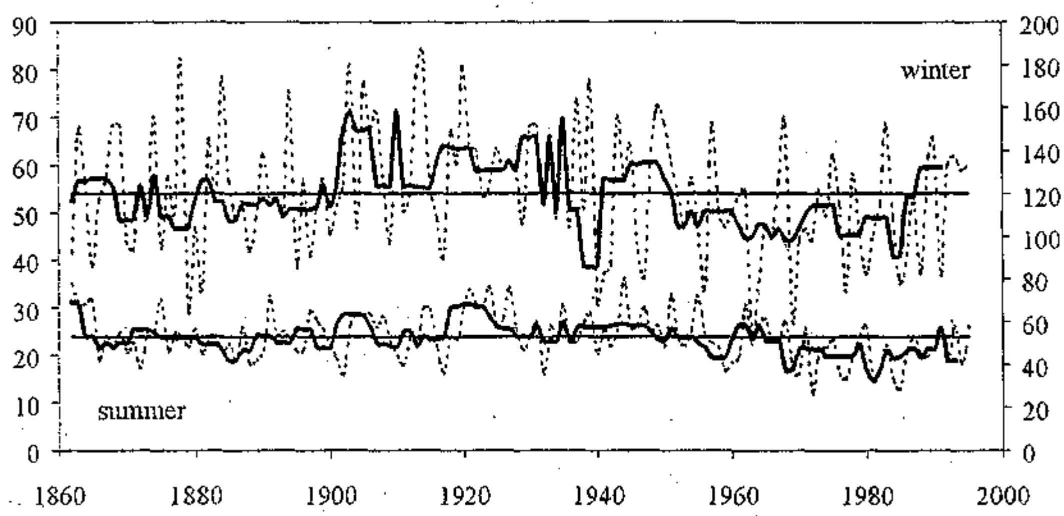
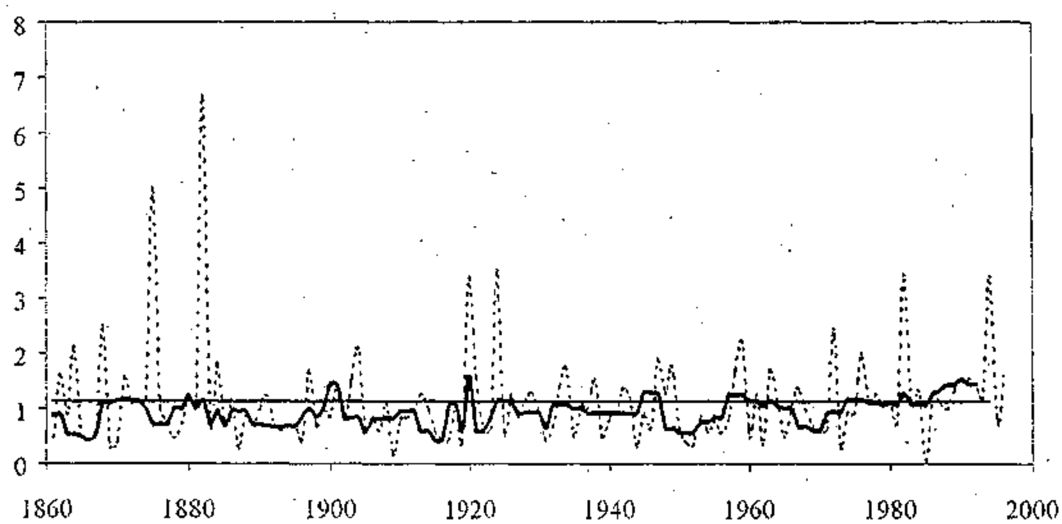


Figure 2.12 Ratio of southerly to northerly weather



2.4 CLIMATE OF THE LUNE CATCHMENT AREA

The River Lune is situated south east of the Lake District with the upper catchment bordering on the eastern Fells of the Lakes; the catchment location is shown in figure 2.13. Average annual rainfall over the entire catchment is about 1460 mm. The distribution of rainfall with topography is shown in Figure 2.14. Approximately 40% of the catchment is upland (over 300 m) and subject to orographic enhancement of rainfall. Figure 2.13 shows that the 300 m contour coincides with annual rainfall totals of approximately 1500 mm, such that 40% of the catchment receives in excess of 1500 mm per year, maximum altitudes are approximately 600m. It is worth noting that even in the upper catchment rainfall is on average 1000 mm less than that in parts of the Lake District which have average annual totals in excess of 3000 mm (e.g. Sprinkling Tarn 3708 mm at altitude 600 m). Snowfall may significantly contribute to flooding in the upper parts of the catchment but there are no data available.

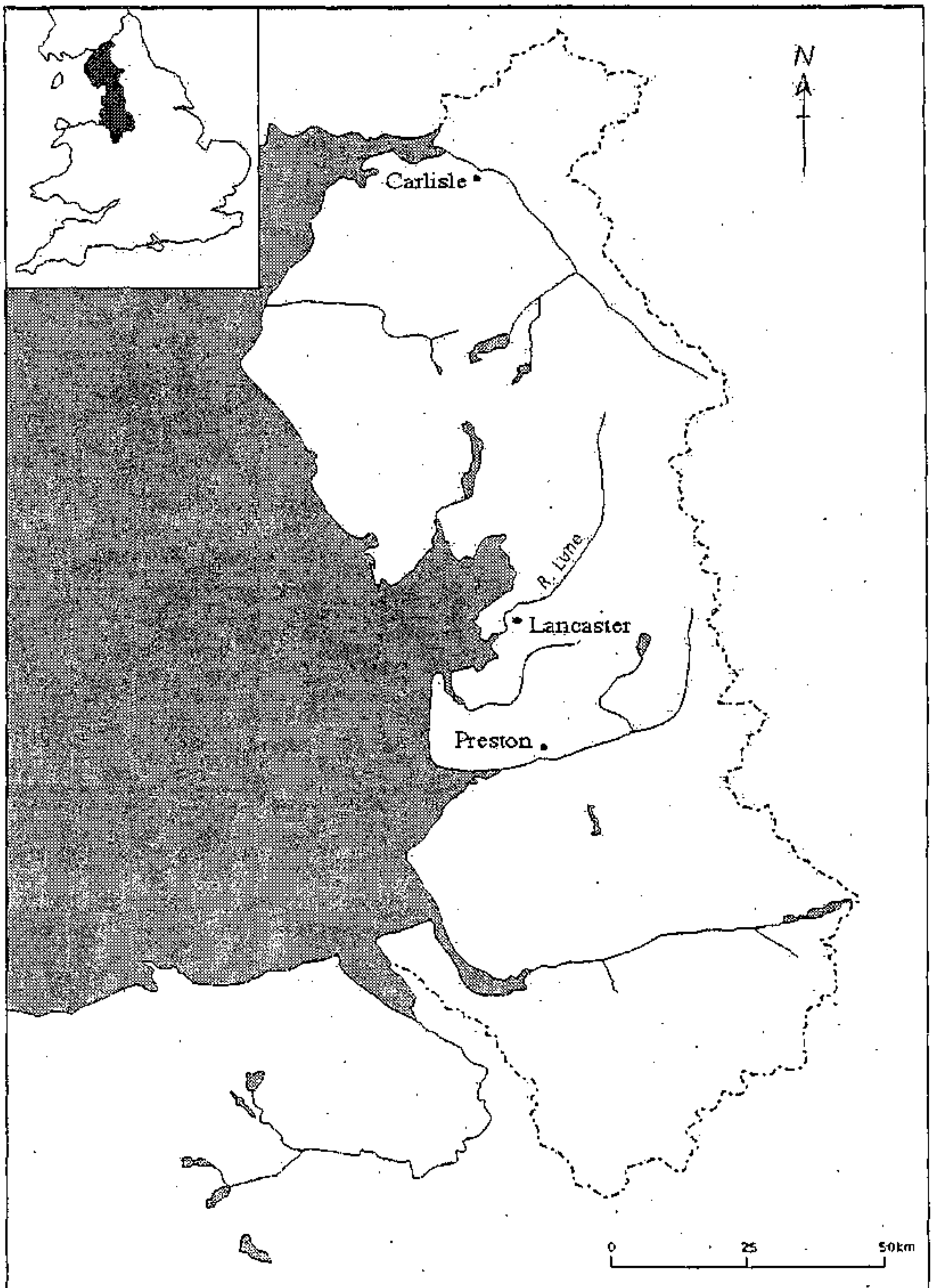


Figure 2.13 North west England and the River Lune

The map shown in Figure 2.14 is based on averages from 26 gauges located within the 100km^2 catchment, however most of these gauges have only short or intermittent records, gauges used for analysis are detailed in Table 2.2 for the Lune catchment.

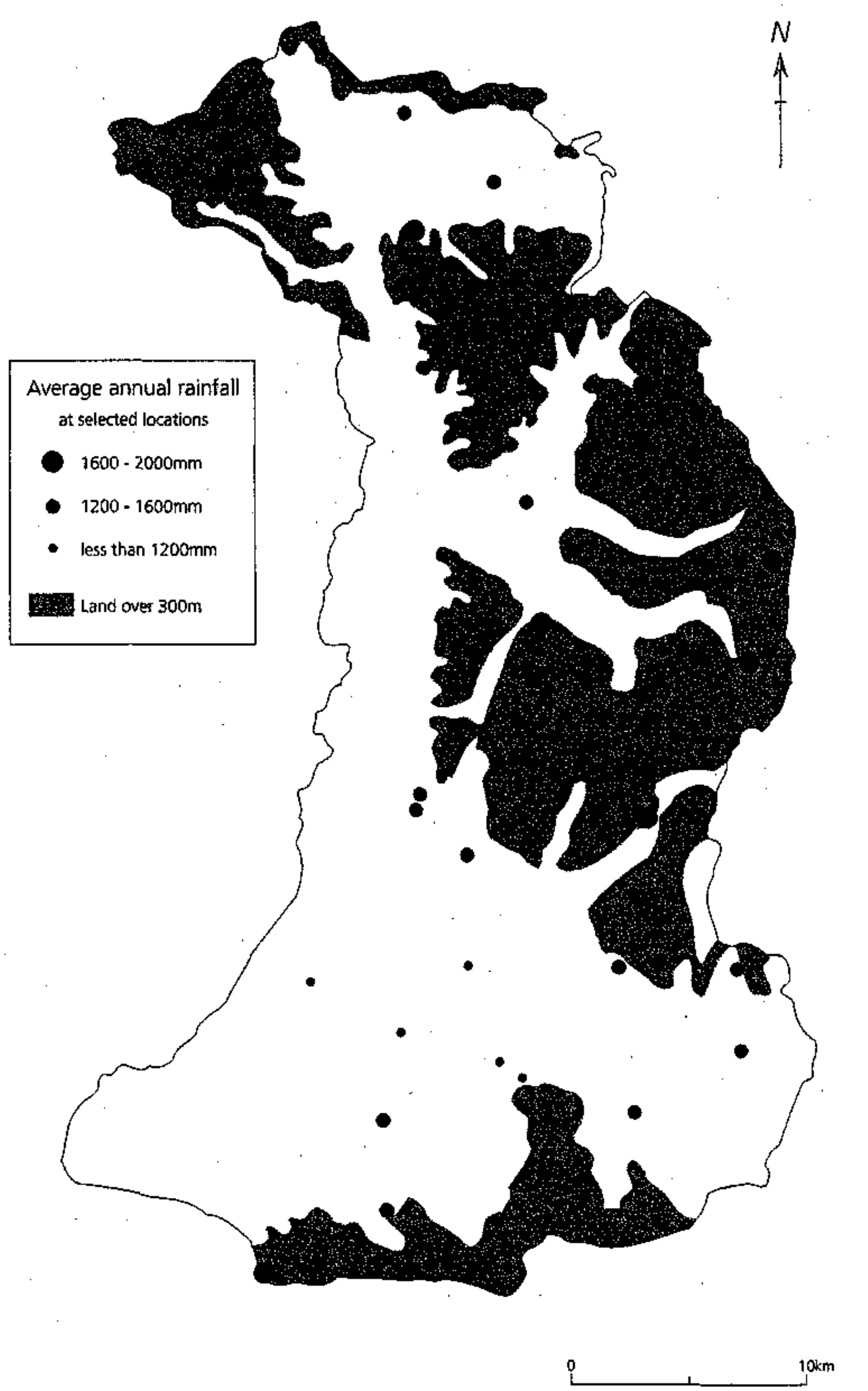


Figure 2.14 Rainfall distribution in the Lune catchment

Table 2.2 Rain Gauges in the Lune Catchment

Gauge no.	Name	Grid ref.	Alt.(m)	Start	End	Years
580057	Orton Shallowford	NY626083	235	1982	1995	14
580664	Ravenstonedale	SD728969	283	1973	1995	23
581358 581059 581025	Sedbergh, Brigflatts Sedbergh Sedbergh, Fairfield	SD642912 SD653919 SD677918	93 123 130	1920 1961 1979	1960 1983 1997	76
584480	Killington	SD592908	204	1961	1993	32
582262	Burton-in-Lonsdale	SD654723	94	1972	1995	24
582903	Bentham	SD675676	160	1972	1995	24
583949 583959 584307	Morecambe Bare Silverdale	SD431645 SD454644 SD463755	7 6 17	1900 1961 1982	1959 1982 1995	95
582407	Arkholme	SD586718	37	1972	1995	24
582626	Austwick Town Head	SD769687	149	1961	1995	34
581631	Barbon	SD639829	210	1930	1942	12
583635	Lune Viaduct	SD482640	20	1930	1959	29

Several of these gauges have been combined to give a longer time series where appropriate; periods of overlap were examined to check that the gauges were giving similar readings. Morecambe and Bare are within 1 km of each other, at the same altitude, Silverdale was the nearest coastal gauge, approximately 11 km north of Morecambe. The record at Sedbergh is comprised of records from three gauges that replaced each other over time.

2.4.1 Annual variability in rainfall

There are no strongly discernible long-term trends in total annual rainfall at Sedbergh, Austwick or Morecambe which represent the upper, middle and lower Lune catchment respectively (see Figure 2.15). All data series presented show rainfall in mm and trend lines are five-year median filter, unless otherwise stated. There is a slight propensity for above average rainfall since the late 1970s. Examination of records from the Lake District is useful because time series exist back to 1870 (Figure 2.16). There appears to be a general decline in annual totals this century with a possible trend reversal around 1970. There is certainly no evidence of increased annual rainfall as reported in Scotland. The Durham rainfall record in north east England appears to show a peak in the annual rainfall series at about 1930 falling continuously until 1960 (Harris, 1985) which, agrees with Gregory's (1956) findings of a general peak in British rainfall between 1920 and 1930. This pattern also appears to be supported by data from Seathwaite and Dalehead in the Lake District, the Sprinkling Tarn gauge is located at a much higher altitude which may explain the difference in trend with a rainfall maximum around 1950. Rainfall at Sedbergh peaks

Figure 2.15 Annual rainfall trends in the Lune catchment

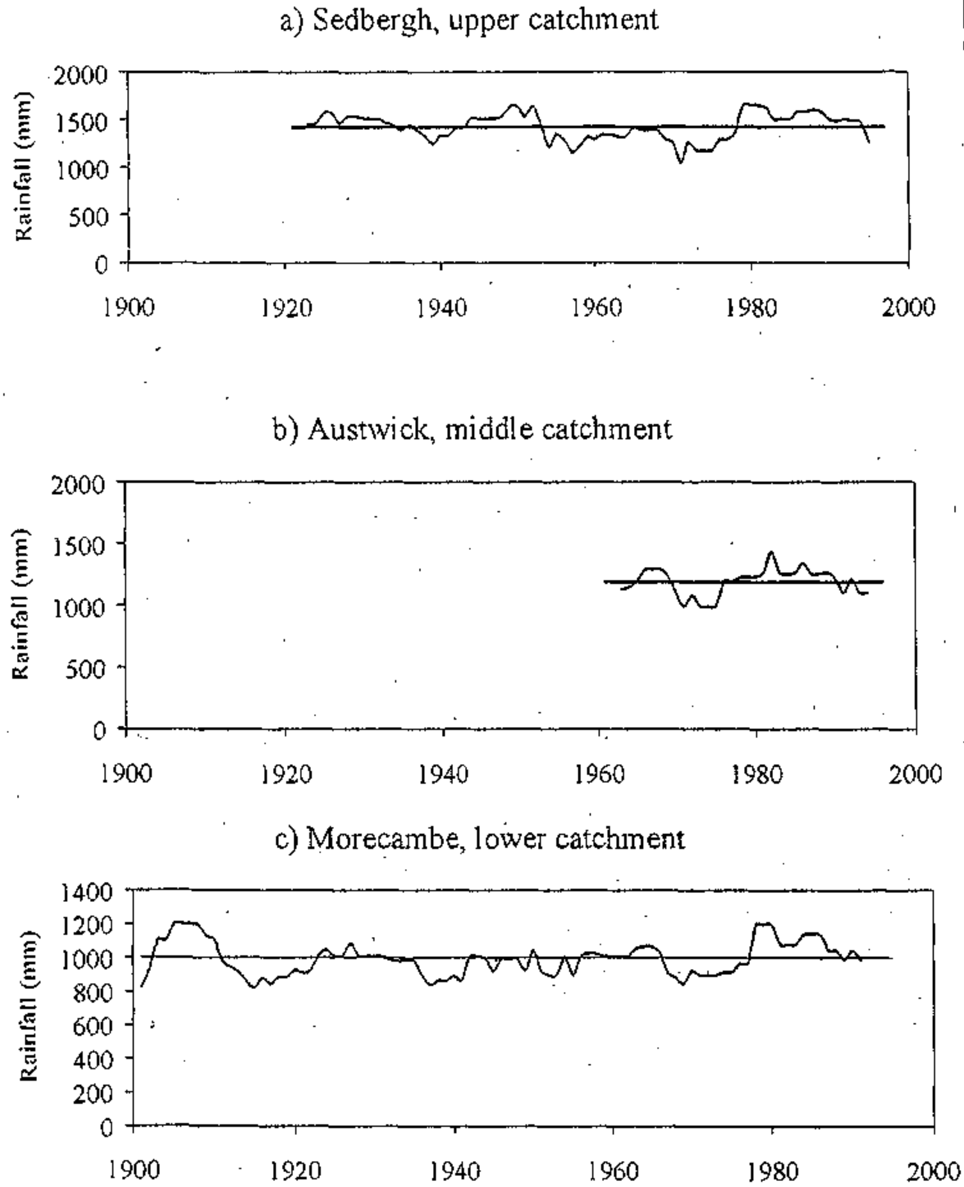
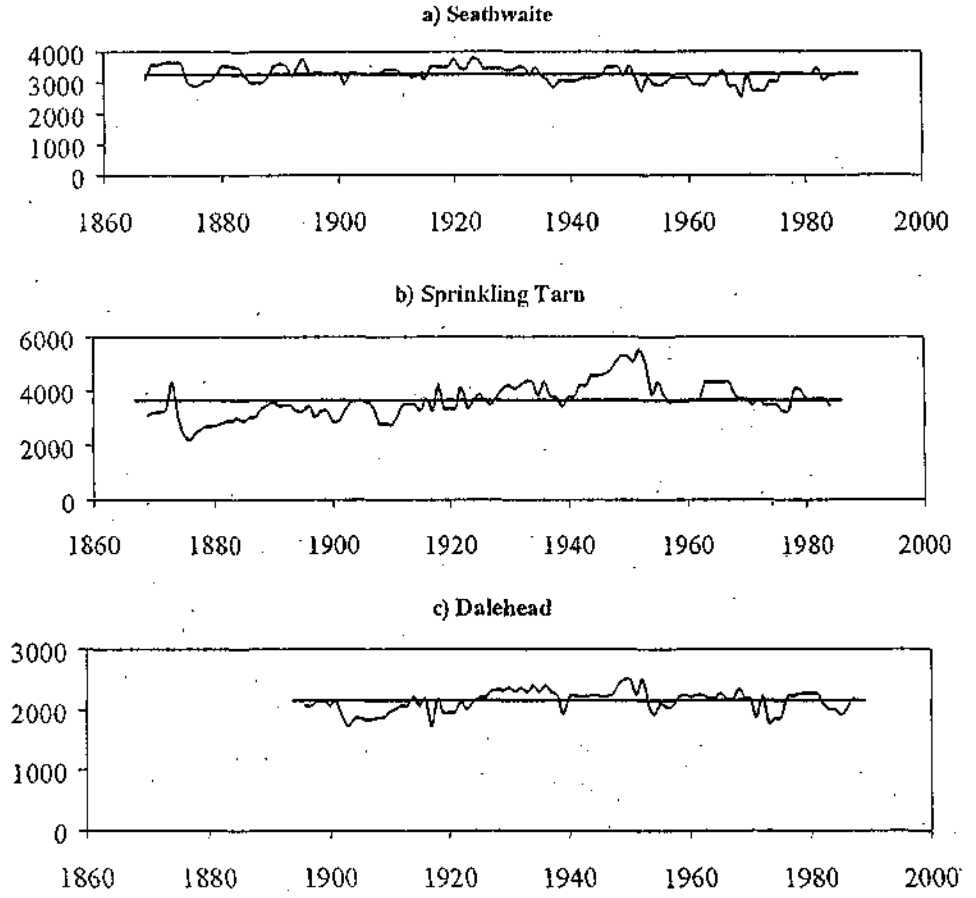


Figure 2.16 Trends in annual rainfall, Lake District

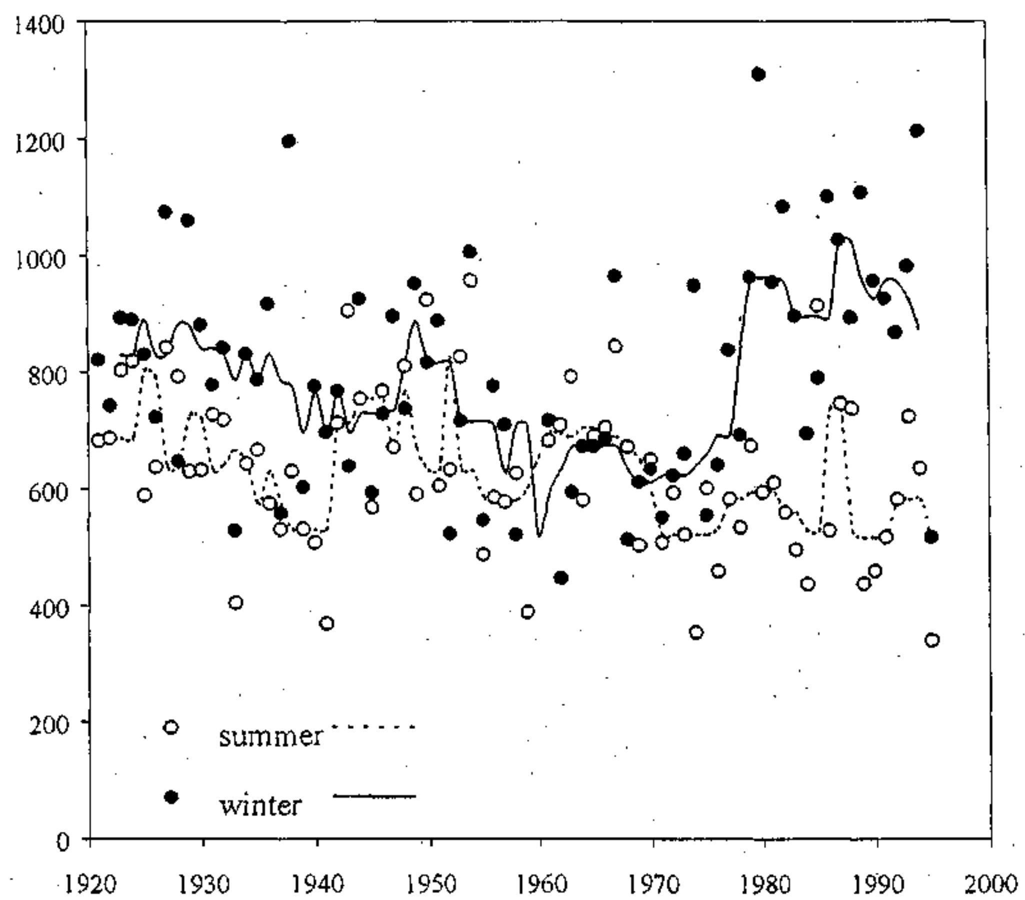


at 1950 and 1980 whereas data from Morecambe show a peak around 1905 and 1980. The data highlight the high spatial variability in rainfall in this area and the importance of orographic enhancement.

2.4.2 Seasonal variability

There are clear trends in the seasonal rainfall within the catchment, shown for Sedbergh in figure 2.17. Considerable divergence in the total amounts of summer and winter rainfall can be seen from the late 1960s. The winter season is defined as the period from October through to the following March and the summer season from April to September. Similar trends in these half-year periods are found at other sites in the upper catchment (Ravenstonedale, Orton and Killington) although these time series are of much shorter duration, starting in the 1960s and 1970s. The distribution of rainfall over the winter period has also changed since about 1970. Figure 2.18 shows the changing monthly distribution of rainfall (figures are actual rainfall totals in mm, not trends) at Sedbergh in the upper catchment. The most notable changes are to the spring rainfall with dramatic increases in March totals in the 1990s and large

Figure 2.17 Summer and winter rainfall at Sedbergh



increases in the April totals from the late 1970s. There has been a downturn in the total rainfall for September and October since about 1980 and some increase in August totals for the same period. The middle catchment is represented by data from Austwick on the eastern edge of the catchment. Analysis of monthly data between 1960 and 1995 show similar increases in total rainfall for January to April, slight reductions in totals from May to September, a large downturn in October and no significant trend for November and December. Data from Morecambe, on the west coast, span a longer period from 1901 to 1995. Rainfall increases can be seen for January, March and April since about 1980 in Figure 2.19. The increase in total rainfall in January, March, April and August observed in the last decade is comparable to totals around 1910. Analysis of longer rainfall records from the Lake District (from 1864-1989) also show peaks in monthly totals around this time (see Figure 2.20, March), unfortunately the data are unavailable after 1989 to compare with the records from the Lune catchment. However it can be seen from Figure 2.19

Figure 2.18 Monthly rainfall at Sedbergh

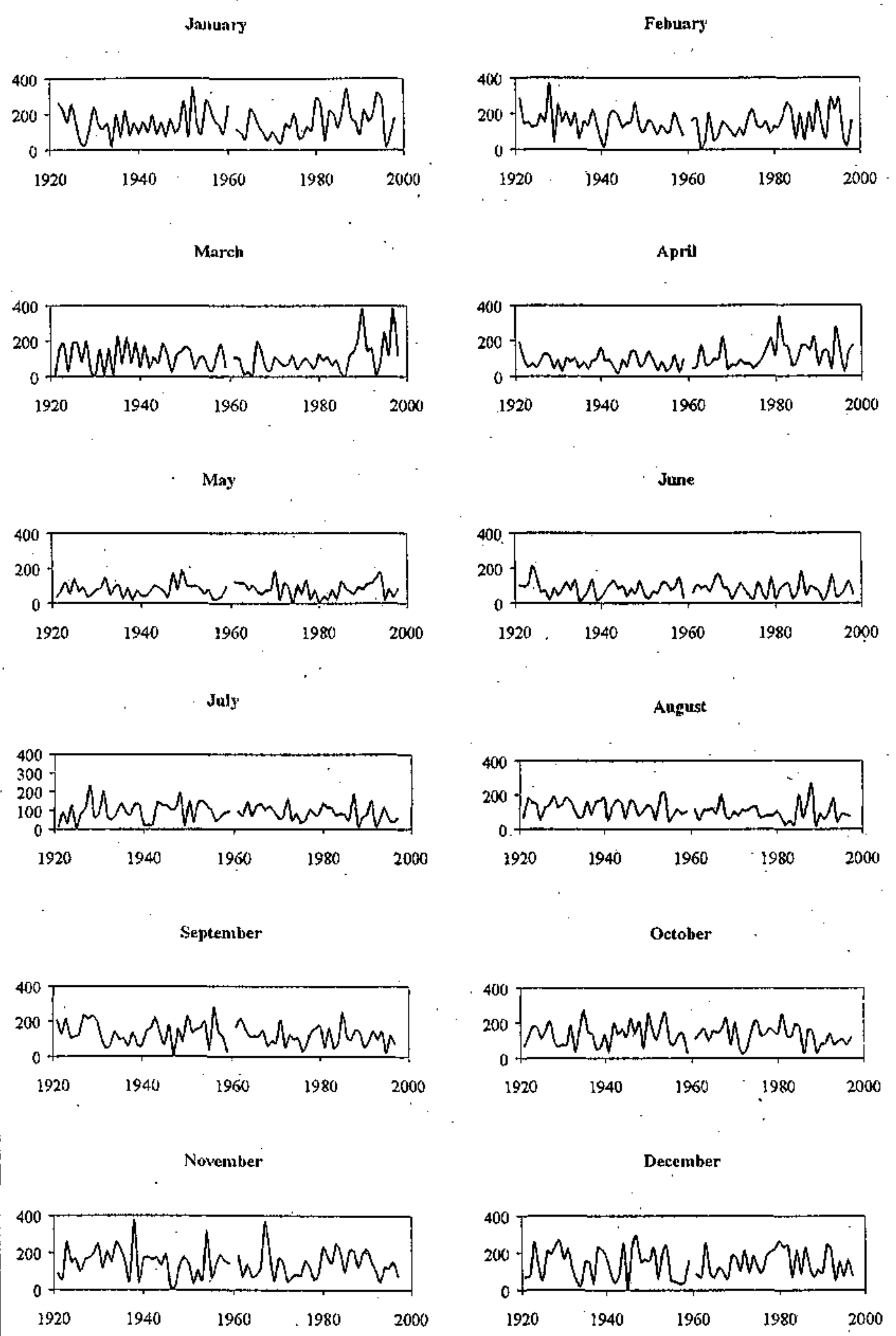
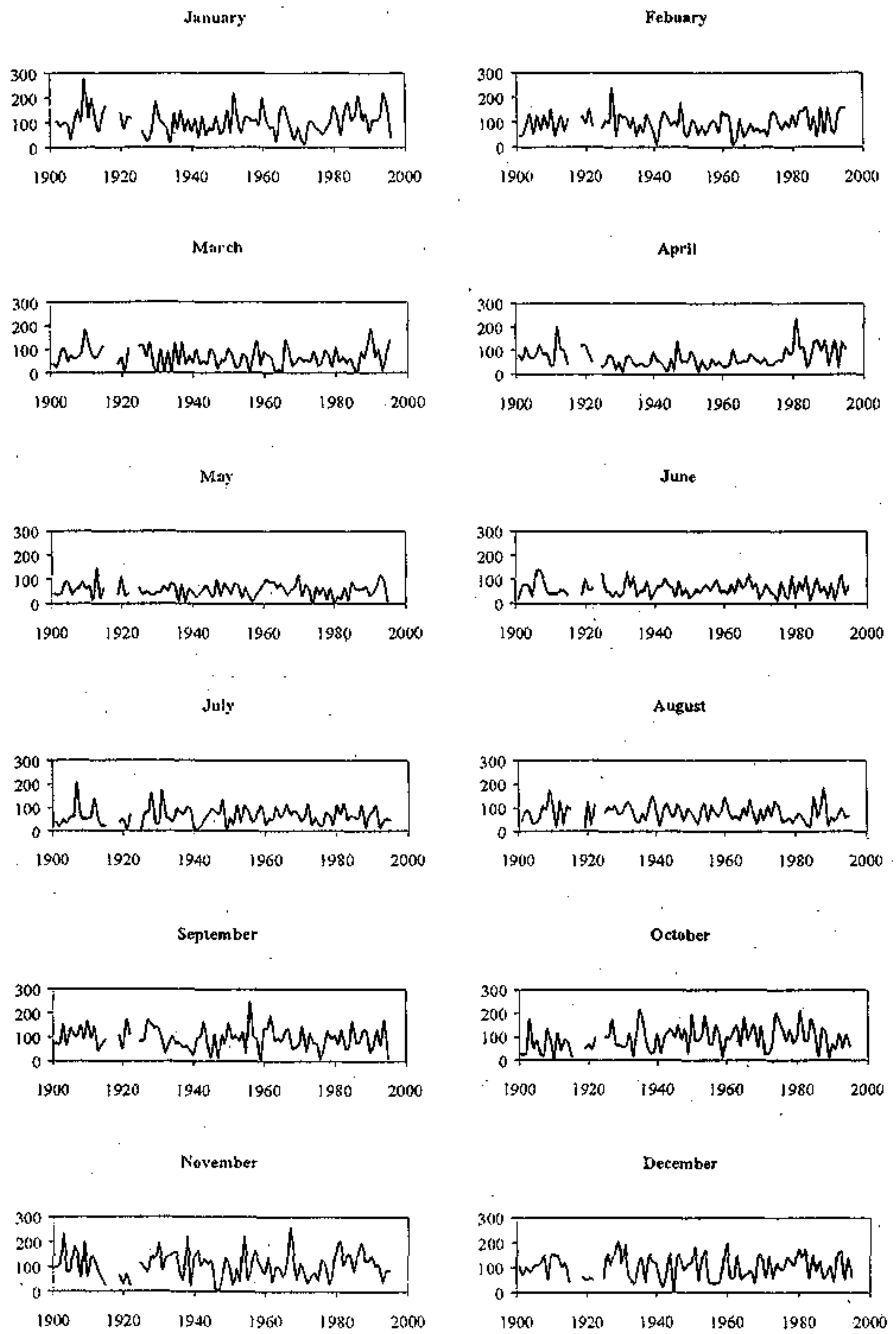
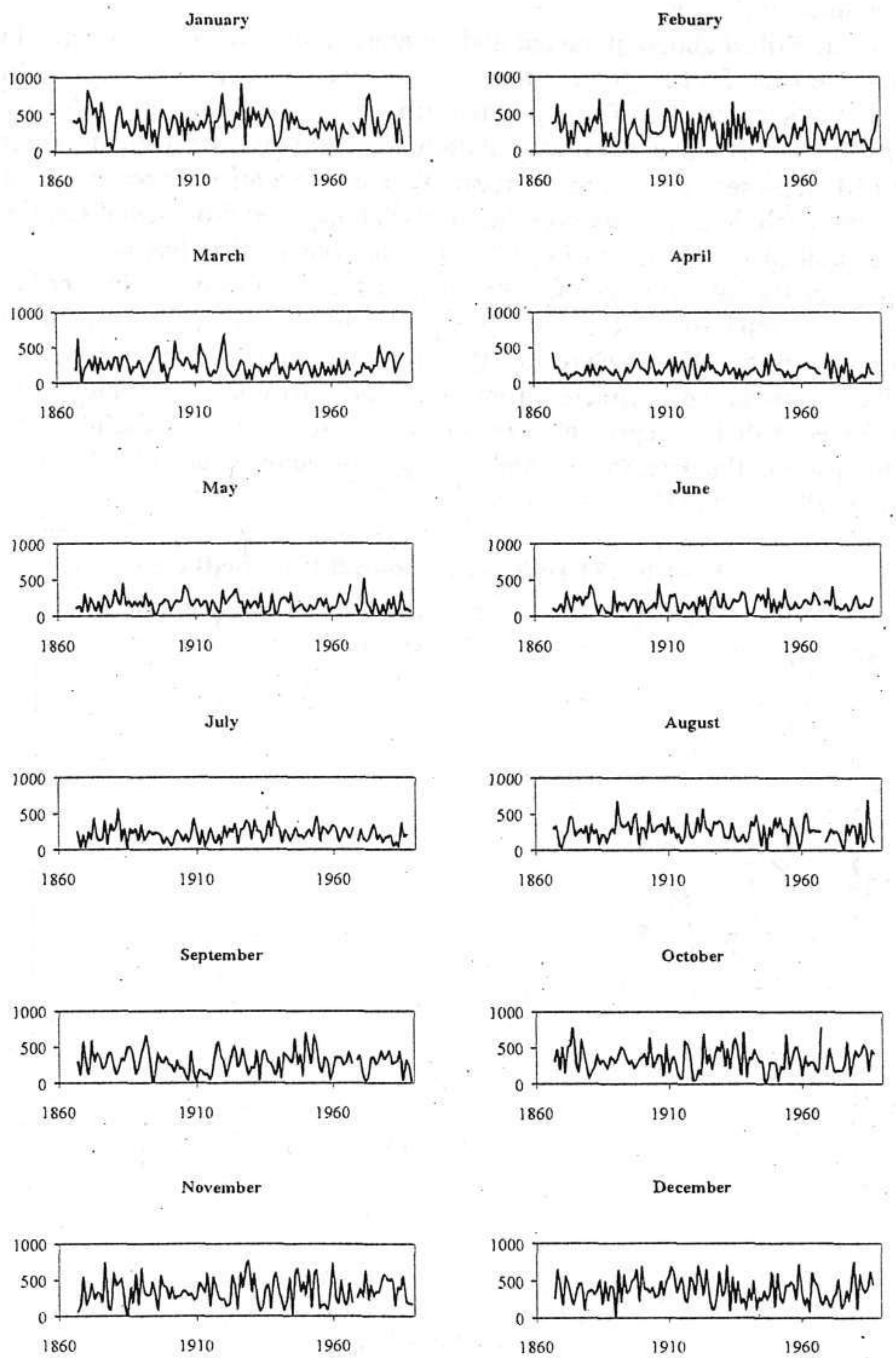


Figure 2.19 Monthly rainfall at Morecambe



January, that there was a similar peak in the data around 1870. Annual trends in rainfall for the Lune catchment most closely resembled the data from Seathwaite in the Lake District.

Figure 2.20 Monthly rainfall at Seathwaite, Lake District



The last twenty five years of rainfall data for the catchment are notably more variable than the preceding fifty years. However evidence from longer data series in the north west suggests that current rainfall trends may be similar to those observed earlier this century around 1910. Previously high monthly rainfall totals can be observed for January, March and April (see Figure 2.18) at Morecambe.

2.4.3 Time Series Analysis

The analysis described above of annual and monthly rainfall trends is affected by the need to impose time frames, for example one month or one year are very artificial time zones. To take account of this problem time series analysis was undertaken to examine subtle trends in data consisting of daily total rainfall. The methods, described in appendix 1, represent a novel application of state of the art time series techniques that have previously been applied to other, non-stationary environmental time series; these are described in Young *et al* (1998). The analysis used is based on the initial identification of the spectrum of the data such that consistent peaks in the data are identified. An example of an auto regressive spectrum for rainfall is shown in Figure 2.21, the spectrum for the raingauge at Sedbergh. The longest time series exists for Morecambe and trend data extracted from time series analysis is presented in Figure 2.22. The green drift line represents the very long-term trend and the blue line the unadjusted cycles in the data, the red line is seasonally adjusted and clearly shows the regular cycles observed in this time series.

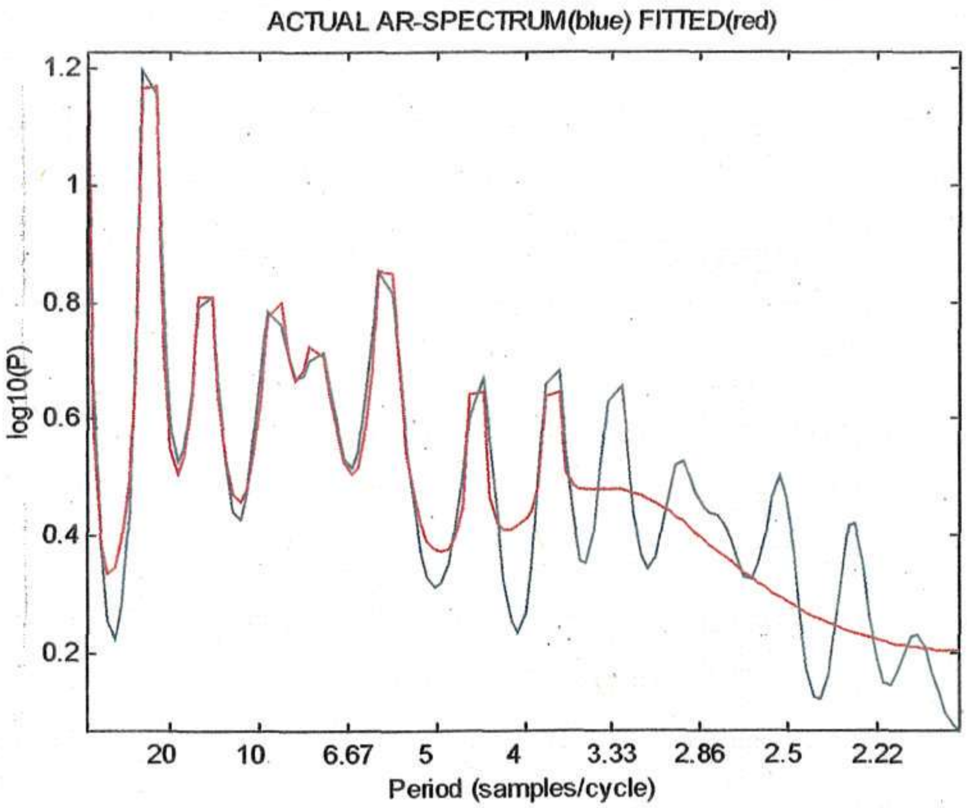
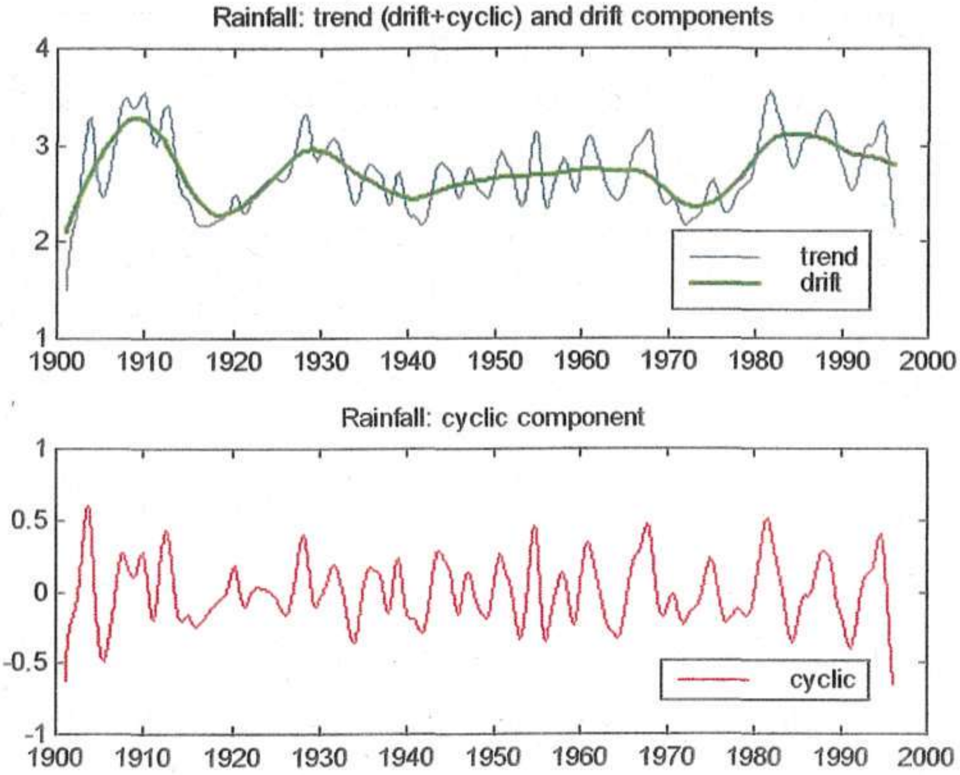


Figure 2.21 Daily total rainfall from Sedbergh

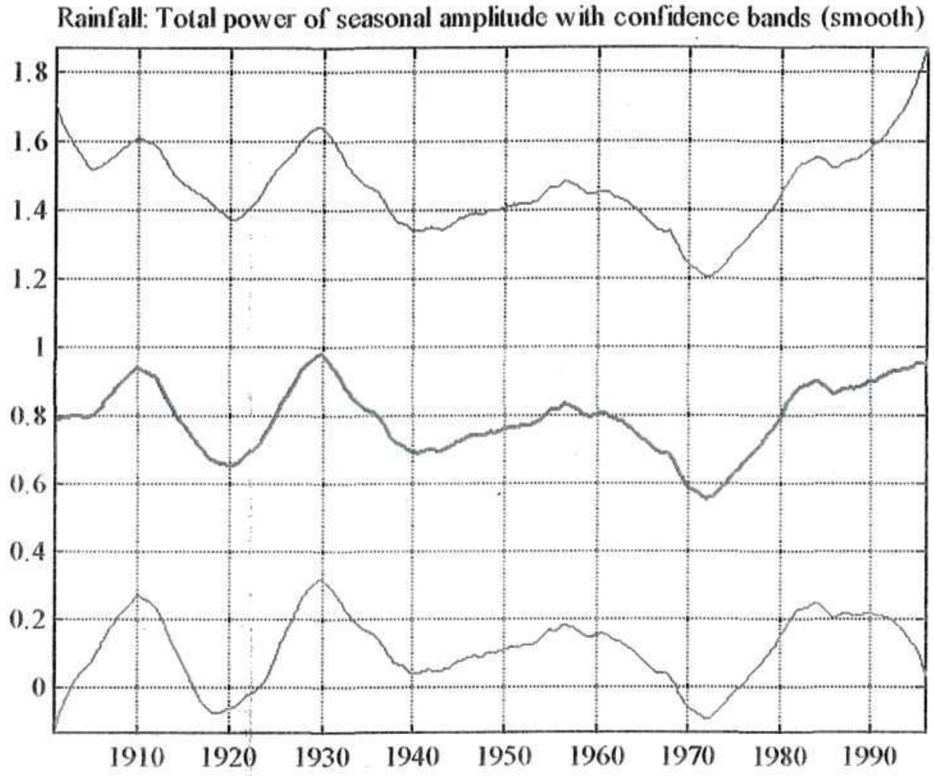
Figure 2.22 Trend data from Morecambe



The cycles shown in Figure 2.22 are visible in the auto regressive spectrum as peaks with a recurrence interval of 3.7 years, a further peak in the spectrum at 6 years may represent the greater interval in the cycle evident over the last thirty years. These cycles are not believed to be artefacts of the processes applied during analysis, however they do require further investigation.

Trends in the seasonal components of rainfall at Morecambe also appear to have regular but much longer cycles (Figure 2.23) which appear to be about 20 years. The feint lines delimiting the confidence limits are subject to end effects; the points at either end should thus be disregarded. The strength of seasonal components in the data is particularly noticeable from the early 1970s.

Figure 2.23 Seasonal trends in rainfall



2.4.4 Rainfall intensity

Predictions for future climate change indicate that rainfall intensity is likely to increase, particularly in winter and wet days are likely to become wetter. It is not possible to obtain a true measure of rainfall intensities from daily total data; however the use of daily totals greater than 15 mm has been selected as a surrogate indicator of rainfall intensity or wetness. Annual rainfall intensity for Sedbergh, shown in Figure 2.24, declined from 1920 to 1970 after which the trend has been upwards but not reaching the same frequency of intensity observed in the 1920s. The trend is similar for winter rainfall, however since 1970 the upward trend in the frequency of intense rainfall has increased beyond the levels at the start of the record in the 1920s (see Figure 2.25).

Figure 2.24 Number of raindays per anum >15mm at Sedbergh

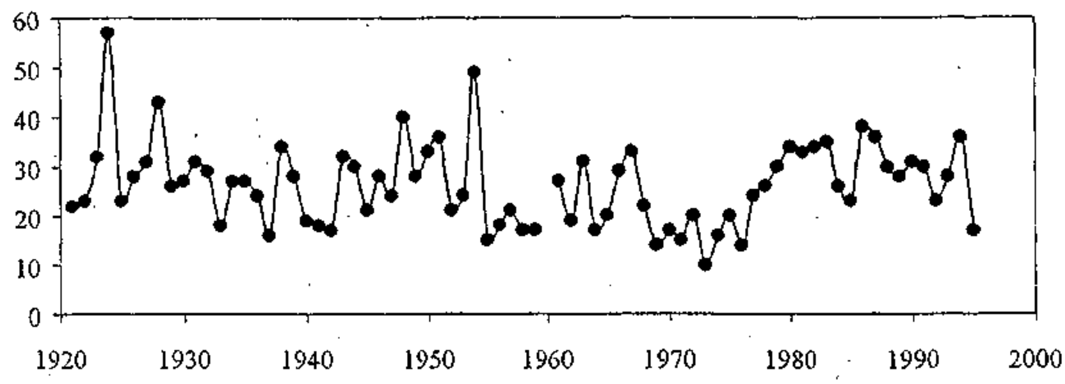
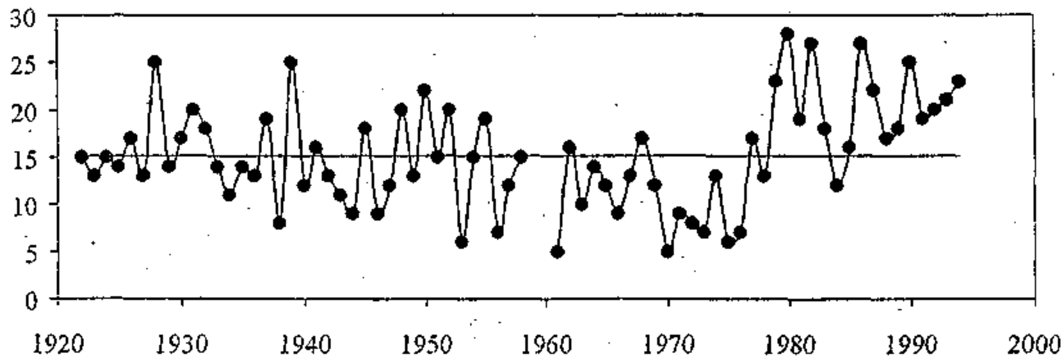
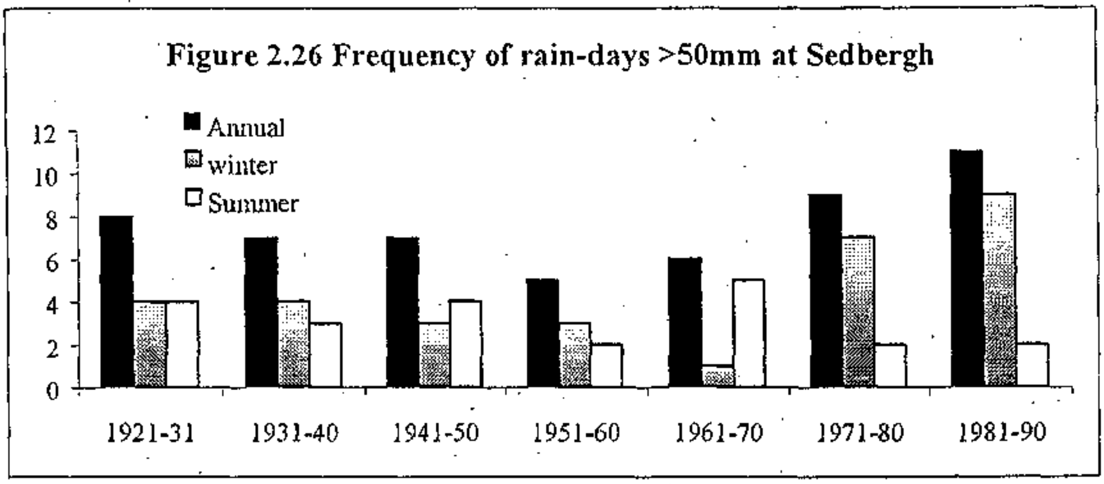


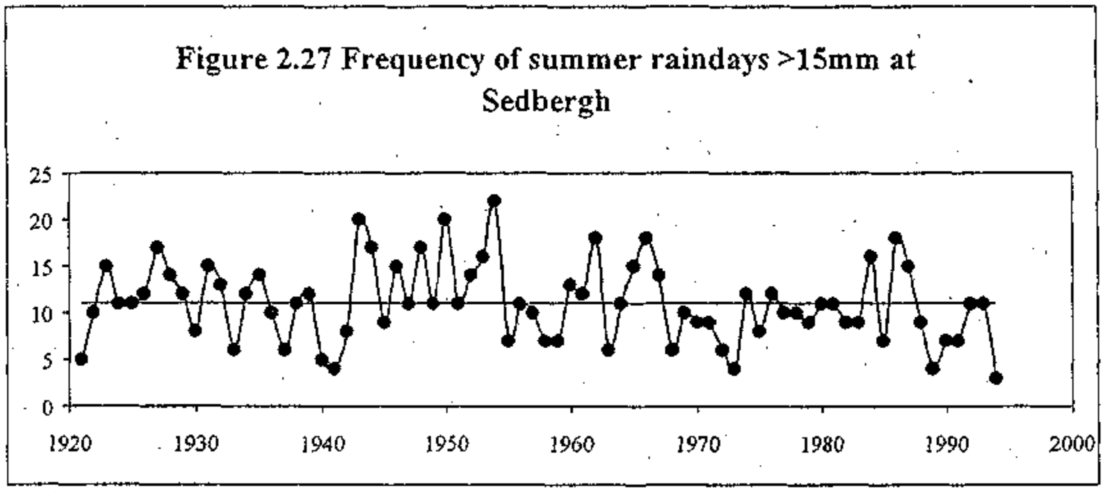
Figure 2.25 Frequency of winter raindays >15mm at Sedbergh



Defining thresholds above which, intense rainfall may cause flooding, or erosion is problematic. Intense rainfall is often restricted to a small area e.g. the intense storm over the Howgill Fells, which caused extensive erosion (Wells and Harvey, 1987) or the Wray floods in 1967 (Duckworth and Seed, 1969) which caused extensive damage locally but did not affect the remainder of the catchment. The January 1995 flood affected large areas of the Lune valley, but worst affected was the flooded village of Hornby where 165 mm fell in the upper part of the catchment in one day. It is known that the rainfall associated with the Howgill floods was in excess of 50 mm, time series for annual, winter and summer rain-days over 50 mm are shown in Figure 2.26. All series shown a decline in frequency between 1920 and 1960 followed by an increase in annual and winter but a continued decrease in summer frequencies. The storm reported by Wells and Harvey (1987) was in June 1982 and was considered to be a one in one hundred year event but possibly even a one in three or five hundred



year event for the smaller valleys affected. Summer rainfall intensities for the period of record at Sedbergh over 15 mm, show a general decline in frequency, the large event in the Howgills was so localised that it was not registered as unusual at the nearby Sedbergh gauge (see Figure 2.27). Clearly intense storms are important as

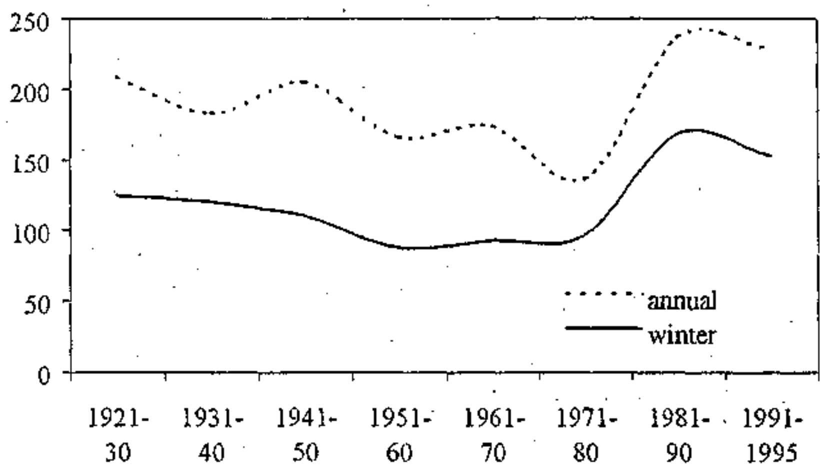


destructive events particularly in upland environments three recent such events have been during the summer including Hurricane Charlie (Carling, 1986 and Wells and Harvey, 1987; Carling and Grodek, 1994). Intense, convective storms may be important mechanisms for coupling hillslope sediments with river channels and the impact on sediment supply may be felt for some time. However such storms have little or no impact on extensive flooding in the wider catchment of the Lune. The largest recorded (i.e. since 1894) flood on the Lune occurred on 31st January 1995 after two days of heavy rain with a two day total of 113 mm, the total rainfall for the month prior to this had been 174 mm (the mean for January is 152 mm). The chronology for major floods on the Lune shows all occur during winter, there have been nine rainfall events with a two day maximum greater than 100 mm (gauged at Sedbergh in the upper catchment), seven of them have led to major floods on the Lune. Notably the two storms not followed by major floods occurred in August and October when the ground is unlikely to be saturated (see Table 2.3). There is a trend towards increasing frequency of medium sized flood events (see Section 4), rainfall associated with these floods, calculated for the period 1979 to 1995 is generally in excess of 30 mm over two days. Figure 2.28 shows the annual and winter decadal frequency of two-day rainfall

Table 2.3 Two-day rainfall totals greater than 100 mm at Sedbergh

Date	Rainfall	Associated flood
14/11/23	113.5	F
03/11/27	131.3	F
03/12/54	112	F
24/03/68	104.9	F
01/08/74	124	
02/10/74	178.9	
04/01/82	108.9	F
20/02/90	112.6	F
01/02/95	113.3	F

Figure 2.28 Frequency of two-day rainfall >30mm



intensities greater than 30 mm at Sedbergh. Since the early 1970s the frequency of 2-day rainfall greater than 30 mm has increased, this increase is relatively greater for the winter half year. In order to compare recent rainfall intensity increases with previously high periods of annual rainfall the record from Morecambe is examined as this record includes the peak in annual rainfall around 1910 (see Figure 2.29). At Morecambe the recent increase in winter rainfall intensity is less significant than peaks in the series in 1910 and 1930. The 2-day totals of rainfall at Morecambe (see Figure 2.26) on a decadal scale illustrate that the potential for flooding has been higher in the 1980s and 1990s than previous decades this century. If the predictions for climate change are correct then it is likely that increased variability in seasonal rainfall and rainfall intensity will be more obvious in upland areas; thus the difference between the winter rainfall intensities at Sedbergh (Figure 2.25) and Morecambe (Figure 2.29) may be explained.

Figure 2.29 Frequency of winter raindays > 15 mm at Morecambe

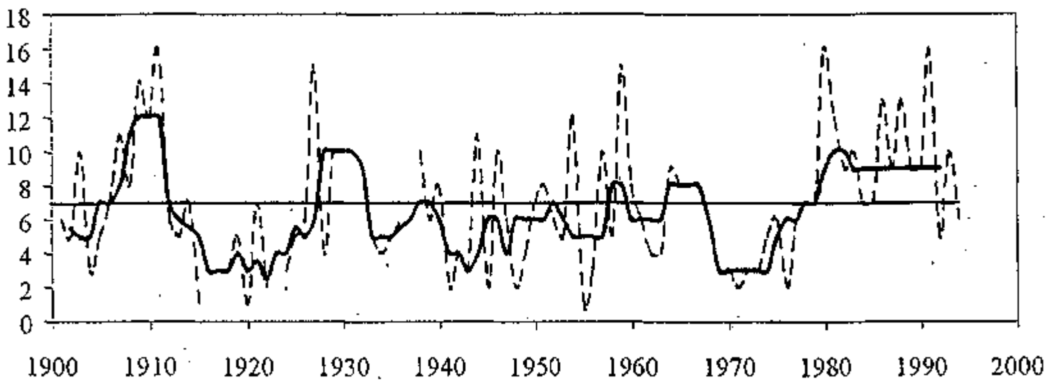
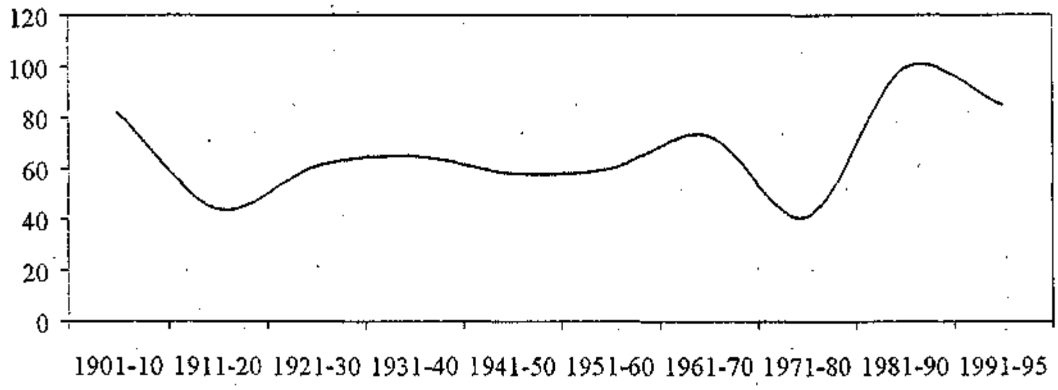


Figure 2.30 Frequency of 2-day rainfall > 30 mm at Morecambe



2.4.5 Local correlations with weather types

In order to investigate the driving mechanisms for rainfall in the Lune catchment correlations have been made with some of Lamb's weather types. The most significant weather types for flood generation in the Lune catchment are likely to be those that are prevalent in late autumn. This season is characterised by cyclonic and other stormy weather types, generally in October-November. The period from about the third week in November to mid-January is characterised by westerly weather types giving mild stormy weather (Lamb, 1950).

Correlations with specific weather types and indices are shown in Table 2.4 for the raingauge at Sedbergh.

Table 2.4 Correlations between weather types and rainfall

Annual rainfall	W Index	AC	C	SW
1921-30	0.38	-0.75	0.09	0.03
1931-40	0.77	-0.73	-0.07	0.24

1941-50	0.87	-0.42	0.40	0.44
1951-60	0.92	-0.69	0.45	0.14
1961-70	0.35	-0.39	0.03	-0.24
1971-80	0.08	-0.67	0.78	0.35
1981-90	0.33	-0.45	0.02	-0.13
Winter rainfall	**Winter W Index**	**Winter AC**	**Winter C**	**Winter SW**
1921-30	0.66	-0.61	0.02	0.56
1931-40	0.81	-0.75	0.01	0.10
1941-50	0.49	-0.61	0.41	0.22
1951-60	0.44	-0.76	0.67	,0.53
1961-70	0.95	0.06	0.25	-0.46
1971-80	0.21	-0.61	0.38	20
1981-90	0.40	0.03	-0.35	-0.4

The highest correlations are in winter with the winter westerliness index. Cyclonic weather types have been most closely related to rainfall between 1940 and 1980. Correlations are more revealing for periods of intense rainfall or wet days (> 15 mm per day) with 43% of wet days preceded by westerly weather, 21% cyclonic, 11% cyclonic westerly and 7% south westerly. Prior to 1970 53% of the rainfall at Sedbergh > 50 mm was the result of westerly air-types; after 1970 20% of heavy rainfall was preceded by westerlies and 45% by cyclonic and south westerly combined.

2.4.6 CORRELATIONS WITH LONG TERM INDICATORS

On a decadal scale annual precipitation at Sedbergh and annual values for the NAO have a correlation coefficient of 0.67, winter rainfall averages on a decadal scale have a correlation of only 0.55. However decadal mean annual NAO and winter rainfall gives a correlation of 0.85; thus the long-term trend in the NAO Index is a good indication of winter rainfall trends in this area. Exploratory examination of the long-term rainfall record at Morecambe using time series analysis (Dynamic Harmonic Regression) has found distinct cycles in the record which may well be related to similar scale fluctuations in the NAO. Given that these cycles are believed to be robust, the possibilities for forecasting ahead are possible and could provide key information for flood forecasting. Correlations with the Gulf Stream are problematic since meaningful correlations are only found with one or two year delays in the data. As discussed previously there may well be a physical justification for undertaking rainfall analysis with a delayed Gulf Stream Index but until such process mechanics are resolved in more detail the analysis is highly speculative and not presented here.

2.5 DISCUSSION

Hydrological variability has been notable in the last few decades and once account has been made of the elevated temperatures and associated evaporative demands, there is no modern parallel to the conditions recently experienced. Knox (1984) suggests that the magnitude of anomalous mean annual temperatures need not be great to produce significant hydrological adjustments provided the trends are persistent.

In all seasons, northerly airflow brings cooler temperatures and southerly airflow, warmer temperatures. Anticyclonic types are associated with warmer summers while in winter easterly weather types bring cooler weather, westerly types are associated with milder temperatures. High values of the NAO Index indicate the strength of flow from the Atlantic associated with warmer weather although this is only significant in winter (Jones and Hulme, 1997). Short-term increases in British Isles temperatures require a change in the mix of circulation types e.g. greater southerly days with respect to northerly days. Longer-term temperature increases over several decades would lead to increased sea surface temperatures around the British Isles so that cold air from the north for example would be relatively warmer. Changes in circulation types would then be unnecessary to create a warmer British Isles climate (Jones and Hulme, 1997).

Rainfall is closely related to the North Atlantic Oscillation if the current trends in the oscillation continue we can expect a greater amount of rainfall to occur in winter. Increased winter rainfall (or rather a greater % of the total rainfall in winter) when evaporation losses are modest, would be expected to increase overall runoff and generally bring benefits for water resources. However, the recent past has also been typified by consistently high temperatures, the last 10 years taken together are the warmest of any 10 year sequences in the Central England Temperature (Green and Marsh, 1997). Elevated temperature can lead to reduced average runoff (LeRoy, Poff *et al*, 1996).

It is of major importance that we better understand the dynamics of Atlantic fluctuations, study their predictability and quantify their impact on weather and short time scale climate variability. Positive phases of the NAO bring stronger westerlies to Britain keeping cooler polar influences away especially during winter. Years of low values of the NAO Index are usually associated with weaker westerly winds and lower European temperatures. Over the last two years the NAO has made its sharpest reversal on record to a lower value, despite the associated continental cooling of Eurasia and northern Europe, global temperatures remained above average. The argument presented is that if high temperatures persist during negative phases of the NAO, it would offer support to the theory that anthropogenic activity is disrupting the global climate system (Michaels, 1997).

It is likely that anthropogenically driven climate modifications will in practice exaggerate the effects of normal environmental changes. There is evidence of rapid and sudden changes in climatic conditions in the past, notably the Younger Dryas to Holocene stepwise change around 11 500 BP which is believed to have occurred over a few decades (Adams *et al*, in press). Although the precise cause of previous sudden climatic changes (over the last few million years) is not well understood, all the evidence indicates that most long-term climate change occurs in sudden jumps rather than incremental changes. Adams *et al* (in press) notes that this relatively rapid nature of change is one of the most surprising outcomes of studying Earth history and the implications for man and the environment have barely been explored.

2.6 SUMMARY

Increased storminess in the north east Atlantic and the North Sea combined with increased winter rainfall and temperatures have been widely reported for the last few decades. Increased winter rainfall and temperature have also been reported for the Lune catchment during the same time period. If the current trends in the NAO continue these trends are likely to become more exaggerated. Winter rainfall in the Lune catchment has a correlation coefficient of 85% with the annual variability in the NAO.

Rainfall gradients across the UK have become steeper over recent decades related to the strength of westerly (and south westerly) airflows which increases the effect of orographic enhancement of rainfall particularly on west facing hills. The result of increased orographic enhancement will lead to greater rainfall intensities, observed in the Lune catchment over the last 25 years. If the current trend in westerly weather continues, the rainfall trends described above are likely to accelerate so that seasonal differences will be greater and wet days will become wetter. The increased winter rainfall is greater and more intense on the upper parts of the Lune catchment than those at lower altitudes.

There is some further evidence of increased variability in rainfall over the last three decades. Distinct cycles have been observed in the rainfall record for the last 100 years which have a frequency of 3.7 years, recently this has increased to 6 years. There is also a cycle in seasonal rainfall trends that occurs every 20 years. These cycles may be related to the NAO and could provide valuable forecasting for rainfall and flooding in the future.

SECTION 3 LAND USE CHANGES

3.0 INTRODUCTION AND OBJECTIVES

This study concerns land use changes at two scales, the catchment and the riparian zone or river corridor. Research has tended to concentrate at the later scale, as local effects are obvious and more immediate. However large-scale catchment land use changes over longer time periods are more significant in terms of increases and decreases in water and sediment discharge.

This section aims to describe and characterise the succession of land use changes within the Lune catchment. Particular emphasis will be placed on the recent (post-war) changes in agriculture and the likely impacts on the catchment in terms of erosion processes and runoff changes. The importance of upland land use, overgrazing and the impacts of drainage will be considered.

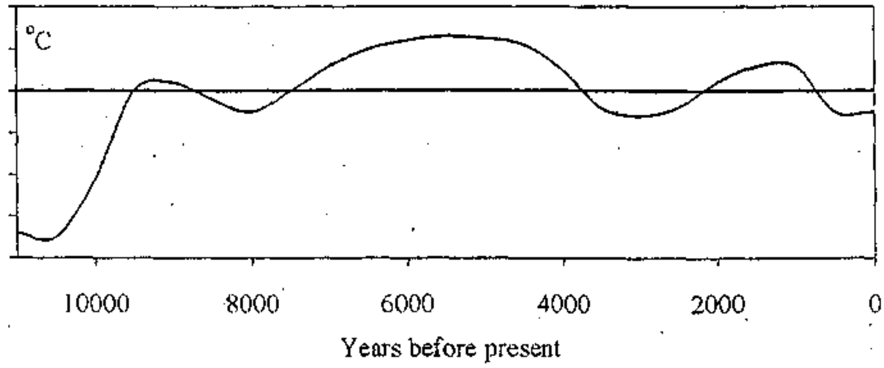
Gregory and Madew (1982) discuss the changing spatial distribution of sediment within catchments as being largely due to anthropogenic effects: building or mining activities, fires, deforestation and increased cultivation. Changes in the Scottish Highlands resulting from overgrazing have been described (Fenton, 1937; McVean and Lockie, 1969); this work specifically addresses accelerated erosion as a result of grazing pressure. However there has been little discussion on the impacts of upland overgrazing on hydrology. Small catchment studies have provided some insight (Heathwaite *et al*, 1990 and McColl, 1979), but the impacts in larger catchments on the hydrological regime are not well reported. It is generally assumed that increased grazing pressure and hence loss of upland vegetation leads to increased runoff, the precise nature of these changes requires investigation.

Changes in water discharge will result from changes to the drainage network. Drainage network changes occur from direct modification of channels (channelisation) or the less obvious extension of networks by forest drainage, field under-drainage or moor gripping (upland drains).

3.1 VEGETATION CHANGES

Vegetation changes have taken place at two timescales: as a result of climate change, notably the associated long term increases in temperature since the last glaciation (Figure 3.1) and also as a result of shorter term anthropogenic activities. These changes are discussed separately.

Figure 3.1 Generalised temperature trends with present day mean (after Houghton *et al*, 1996)



3.1.1 Long-term post glacial and land clearance adjustments in vegetation

The last glaciation in Cumbria ended about 12 ka BP (14 ka BP in south Lancashire) after which trees were able to recolonise the area. Natural forest (wildwood) reached its climax stage about 6 ka BP after which time Neolithic peoples began to transformation of the countryside. It is estimated that wildwood had disappeared from most of Britain by 2.5 ka BP (Rackham, 1986). Gradual clearing of woodland was ongoing until about 600 BP when natural woodland had reached what is close to its present extent; this does not include the reafforestation with conifers in the twentieth century.

Peat formation in the British uplands began in hollows 8.5 ka to 7.5 ka BP but only became widespread after deforestation led to reduced evapotranspiration and increased water logging of soils (Evans, 1992). These changes would also have led to increased runoff and hence destabilisation of stream channels, bank erosion and headward extension of channels. In the uplands erosion took place when woodland was cleared. However once grassland heath or moorland was established the slopes and channels would have stabilised and probably have altered little since, as sensitivity to erosion diminishes as soon as vegetation cover is established (Evans, 1993). This is not the case where there has been large scale erosion of peat in recent times (last 100 years) in some upland locations in Britain. There is some evidence of post-glacial erosion in the Howgills, northwest England, (Harvey *et al*, 1981; Harvey, 1985) in the form of gullying, this is supported by evidence of layering in present day erosion scars (Evans, 1993).

The vegetation history of the British Isles is largely derived from pollen records found in lake sediments and peat bogs. For the northwest of England evidence is mainly from the Lake District; however other sources of information come from sedimentary evidence in the Howgill Fells, the source of the Lune, an area comprising nearly one third of the Lune catchment. Harvey *et al* (1981, 1985) have used dating of sedimentary deposits and the development of alluvial debris cones and fans to identify periods of slope instability conditioned by human activity as well as climate change. Earlier work by Cundill (1976) investigating peat bogs in the Howgill Fells, identified four major episodes of woodland clearance. The beginning of the growth of the peat bog c. 3.5 ka BP coincides with one clearance phase within the Bronze Age (4.4 ka

BP –2.7 ka BP). Archaeological sources indicate anthropogenic activity in the upper Eden valley at this time. The second clearance phase dates from before 2290 BP and the third phase occurred during the Roman period (1910 – 1540 BP). The remains of a Roman fort found in the adjacent Lune Gorge are testimony to the Romano-British occupation. The fourth phase is undated but thought to equate with the Dark Ages and the Norse immigration (1540 – 1250 BP).

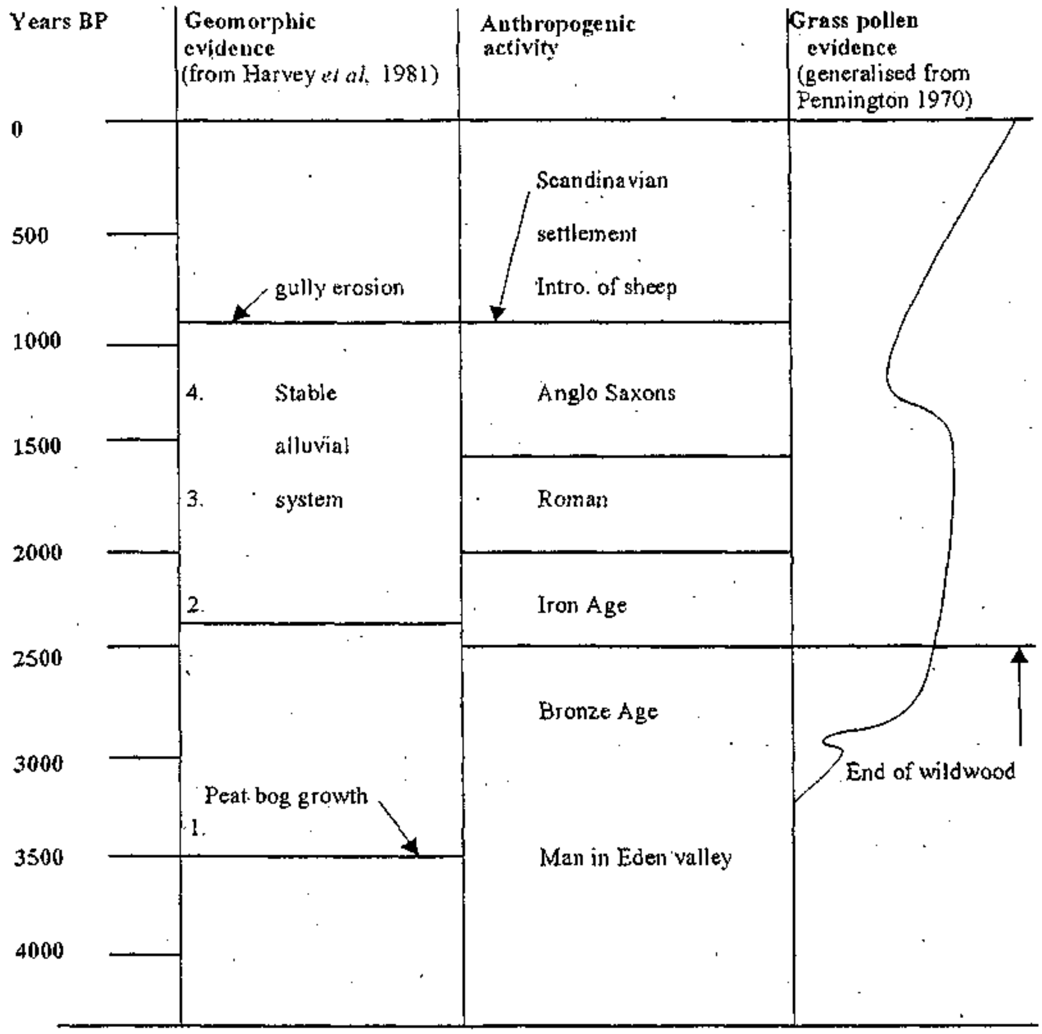
The investigation of a buried organic layer in the Middle Langdales (Howgill Fells) gave a date of 2540 ± 55 BP (Harvey *et al*, 1981). Study of the deposits showed the existence of a stable alluvial system for 1800 years from about 2.8 ka BP to 900 BP. Towards the end of this period there is evidence of disturbance in the form of an inwash of unweathered parent material as gully development began; debris cones then buried the deposit. This gully activity occurred soon after the period of Scandinavian settlement, when most major settlements of the area developed. During this period and the succeeding twelfth century monastic influence, sheep farming was introduced and then expanded and intensified. This contention is strongly supported by pollen evidence from the nearby Lake District. The main expansion of grassland shown in pollen diagrams from the larger lakes and tarns of the Lake District is attributed to the activities of the Scandinavian immigrants and widespread sheep farming (Pennington, 1970). Pennington (1970) further comments that the present poverty of the flora of the Lake District is probably a result of 1000 years of overgrazing by sheep. A summary of the temporal variations in vegetation and anthropogenic influences is shown in Figure 3.2.

The last 1000 years have seen increasing intensification of farming and therefore increased pressure on the land. This intensification has gathered pace in the 20th century and has raised concerns for biodiversity, landscape and soil stability and sustainable use. A recent study of lake sediments from Blelham Tarn in the Lake District have shown that there has been a rapid acceleration in the rate of sedimentation in the Tarn during the last 40 years (van de Post *et al*, 1997). Cores were examined for the period since 1950 and found to contain overwhelming evidence for catchment erosion particularly during the last decade. The study concludes that the increased production of surface soil material is a direct response to increased pressure from sheep grazing. Land use changes over the last one hundred and fifty years from agricultural practices are discussed in the following section.

3.1.2 Impacts of farming on vegetation; the last 150 years

Since the end of the second world war the rate of change in farming practices has been faster than ever before. Rapid mechanisation has increased the amount of heavy farm equipment and led to soil disturbance and particularly compaction. In upland areas and marginal land, drainage has been widespread and traditional diverse management has given way to a monoculture of intensive sheep farming. In the upland area of the Lune, it is the intensity of grazing that has caused the greatest visible change to the landscape. The impacts of overgrazing on vegetation are twofold: loss of cover and diversity and the invasion of undesirable plant species as a direct result of grazing; secondly, the loss of all vegetation as a result of soil erosion. This section will briefly review the soil and vegetation changes resulting from modern farming methods and discuss the state of the British uplands.

Figure 3.2 Late Holocene vegetation and anthropogenic activity in north west England



Periods of woodland clearance (nos. 1 – 4) from Cundill 1976

The extent and nature of soil erosion problems in North America, India, Australia, New Zealand and parts of Africa as a result of over-intensive land use are well documented, highly visible and frequently catastrophic. Much of our knowledge of erosion processes stems from research in these soil sensitive areas over the last 50 years. Until recently soil erosion has not been regarded as a serious issue in Britain, despite early warnings in Scotland (Fenton, 1937). In the British uplands noticeable gully erosion, landslides, screes and bare slopes may often have been dismissed incorrectly as natural processes. Erosion may be initiated by human activity but the resultant feature may resemble an adjacent 'natural' erosion feature. The effects of upland over grazing are becoming all too evident in many parts of Britain as described in the recent report "Crisis in the Hills" (Crofts *et al*, 1996). Since 30 % of Britain is upland (over 300 m) and grazed by sheep, any adverse effects are likely to be widespread.

It is important to make the distinction between natural soil loss and accelerated erosion induced by human activity. The principal forms of erosion in the uplands are sheet and gully erosion (often leading to scree formation), landslips, river bank erosion, poaching by stock trampling and bunker erosion (erosion of deep peat or soil by animal rubbing). Acceleration of these forms of erosion may be caused through a loss of surface vegetation by overgrazing (McVean and Lockie, 1969). Trampling by animals has also been shown to reduce infiltration rates and increase the runoff, which then has the capability of transporting sediment (Warren *et al*, 1986). A summary of some effects of overgrazing is shown in Figure 3.3.

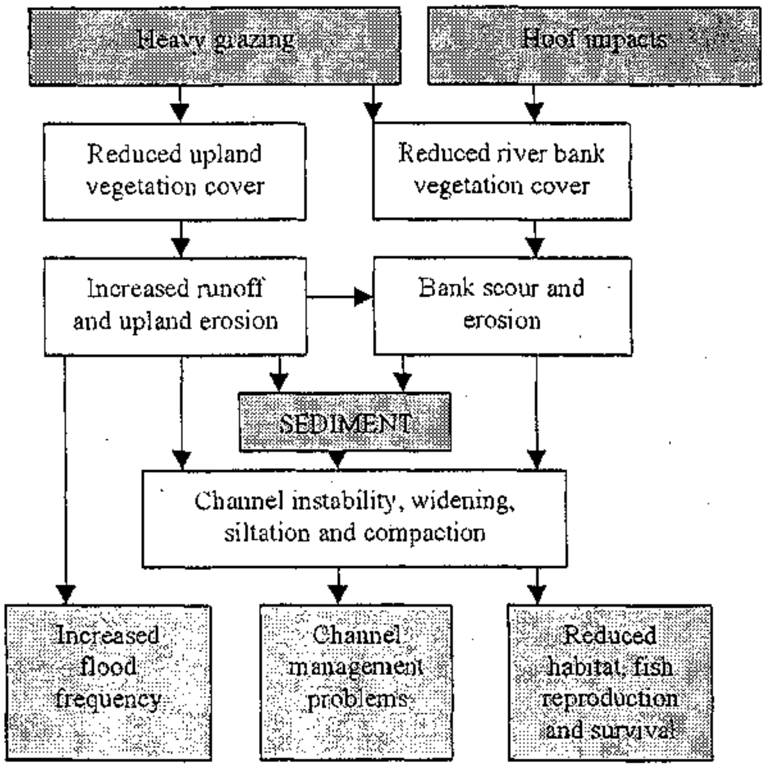


Figure 3.3 Some effects of over grazing

The spatial extent of accelerated erosion in the Britain is very difficult to assess and indeed the need for a national survey has been voiced (Evans, 1997). Clear evidence of grazing pressure has been identified in more marginal areas of the Britain i.e. in upland areas (Crofts *et al*, 1996; Evans, 1977, 1990a, 1992) but the true extent of the problem is not really known. Some confusion has been caused by the definition of overgrazing. Ecologists may use the term 'overgrazing' to describe a situation where natural succession of vegetation is arrested (McVean and Lockie, 1969). In this study overgrazing is defined as a level of grazing where soil is exposed and erosion initiated.

The effects of overgrazing are complex and require an understanding of the interactions between stock management and climate, topography, vegetation and soil. The degree of surface runoff and erosion is dictated by the dispersive effects of raindrops and the amount and velocity of runoff and also by the resistance of the soil to dispersion and mass movement, frost and desiccation. Both processes are influenced by climate through the characteristics of rainfall, by topography which defines the slope gradient, aspect and the area of the catchment, by vegetation and the ability of soil to absorb and transmit water (Baver, 1956; Marshall and Holmes, 1988). The effects of rainfall intensity, temperature (frozen soil in winter and desiccation in summer) and wind, which determines the angle and velocity of raindrops, is offset by a good vegetation cover. Solar energy and wind stress may also be important because they affect evapotranspiration, which in turn dictates the soil moisture content at the time of precipitation.

The type and nature of vegetation affects the rate at which the erosion processes, described above, operate. A thick grass sward or dense forest will intercept a greater amount of precipitation reducing the velocity of runoff and the cutting action of the water. A deep root structure increases granulation, porosity and biological activities. In temperate zones it is generally accepted that a good vegetation cover precludes any serious risk of erosion (Bissonnais *et al*, 1993). However a change in vegetation type that increases runoff will have an impact on isolated exposures of bare ground. There are also important differences between vegetation types in terms of water use that affect total runoff, flood frequency and consequent bank erosion downstream. The range of overgrazing impacts may be observed on a scale from changing vegetation type to complete vegetation removal and soil loss. The more moderate end of this "overgrazing scale" may still cause important changes in the hydrology of affected areas.

Concerns have been raised regarding the decline in a number of important plant species in the Lake District as a result of grazing pressure (Pennington, 1970); the loss of biodiversity is clearly important to the ecology of an area. Change in the existing grass sward may also be significant. Two specific vegetation changes have taken place in British uplands that have particular significance for both erosion and runoff, namely the loss of heather *(Calluna vulgaris)* and the increase in bracken (*Pteridium aquilinum*). The encroachment of bracken invasion into areas previously dominated by heather represents a threat to the ecology, agricultural economy and landscape value of many upland areas in Britain (Whitehead and Digby, 1997). Bracken is an aggressive species widely distributed throughout temperate and tropical parts of the world; it has probably been increasing in Britain since the start of large-scale deforestation (McVean and Lockie, 1969). In woodland bracken is a subordinate species in the ground flora. In the past bracken on exposed hillsides was widely used for animal bedding and was kept partly in check by annual cutting or harvesting. In addition the succession of very cold winters in the late nineteenth and early twentieth centuries may have slowed its spread by killing off stems and young fronds (McVean and Lockie, 1969). It has also been noted that a high ratio of sheep to cattle and repeated moor burning are advantageous to the spread of bracken. The increase in land drainage may also be responsible for the spread of bracken, as it prefers drier land. Areas of dense bracken cover are possibly less at risk of erosion, as sheep only lightly graze these areas. However, given stocking densities are increasing, the spread of bracken may increase the pressure on adjacent grass land. Similarly in areas that have been stripped of heather but not colonised by bracken there is a tendency for matt grass (Nardus stricta) to dominate which has poor nutritional value for sheep. The loss of heather in upland areas has been attributed to overgrazing (e.g. Evans, 1992), repeated cutting and burning. Heather is often lost from an area as a result of damage to peat soils where it is usually found. In some areas peat soils have been damaged by burning (often as part of a moorland management program), drainage, overgrazing and trampling.

Recent findings from English Nature (1998) suggest that an appropriate combination of cattle and sheep grazing is good for the conservation of upland areas not affected by overgrazing. In many areas, particularly in the uplands, the reduction in the number of cattle, due to lack of profitability and more recently BSE, has lead to a deterioration of grassland and scrub invasion. Cattle are less selective eaters than sheep and leave a variety of sward heights: hardy tough-mouthed cattle will eat rank vegetation and they venture into wetter areas. It is believed that more cattle and fewer sheep would help maintain heather and reduce the invasion of bracken.

The distribution and type of vegetation in a catchment is important in hydrological terms because of the different associated rates of transpiration and infiltration. The significance of bracken invasion in the uplands should be assessed in parallel with the loss of heather and changing spatial extent of close-cropped grasses. Climate, topography and soil type play such a major role in the hydrology of an area that it is difficult to generalise about precise hydrological differences between vegetation types. However some tentative conclusions can be drawn. A study in south west England found that heavy grazing of permanent grassland resulted in an 80% reduction in the infiltration capacity; surface runoff from overgrazed permanent grassland was twice that from lightly grazed areas and twelve times that from ungrazed areas (Heathwaite *et al*, 1990). McColl (1979) found runoff volumes to be seven times higher from grazed pasture when compared with ungrazed pasture. The effects of changing land use on the hydrological characteristics of a catchment have been modelled for an upland and a lowland catchment in northeast England (Dunn and Mackay, 1995). The figures are based on the hydrological responses of eight different vegetation groups, which include bracken, grassland and heather moor. The results of the modelling are shown in Table 3.1 (Dunn and Mackay, 1995) and reveal the higher runoff rates associated with bracken.

Table 3.1 Percentage runoff for two catchments under different vegetation types

	Bracken	Grass	Heather
Upland	78	74	75
Lowland	56	51	52

3.1.3 The role of agricultural subsidies in vegetation change

The literature on the ecology of upland areas suggests that continued and sustainable management of the uplands will depend on a sound understanding of upland ecology (Hunter, 1962). Considerable work has been done on the response of different herbaceous plant species to grazing by a variety of herbivores (Maxwell *et al*, 1994; Hope *et al*, 1996). The consensus appears to be that where sheep alone graze a pasture there is a trend towards sward degeneration and loss of species diversity (Hunter, 1962).

In upland areas of Britain sheep farming is the main activity. Farm income is derived in part from the sale of surplus animals and headage payments. Wool is considered of little importance since the value of a fleece is the same or less than the cost of shearing. As upland farm income in the form of subsidies was 49% in 1988 (Econoco, 1988), based on headage payments, the pressure to increase stock numbers is consequently very high. It has been suggested that the condition of pasture in upland areas is proportional to the amount of improved lowland available on farms. If lowland grazing can be improved then grazing pressure on more vulnerable areas (upland and common grazing land) is eased (Bendelow *et al*, 1996).

It is hard to define a stocking density threshold for incipient erosion or accelerated. erosion since it is dependent on many different factors as described in section 3.1.2. The studies mentioned previously in relation to overgrazing and runoff effects do not define overgrazing in terms of stock numbers. Evans (1977) reported erosion as a result of sheep grazing in the Peak District at average densities of 0.5 ha per sheep. Several accounts of erosion by sheep on grazing lands make no mention of specific stock densities (e.g. Kirkby, 1963; Thomas, 1965; Lewin *et al*, 1974). Evans (1977, 1990 and 1992) describes very low grazing densities associated with erosion but it should be noted that Evan's work was on peat soils, which he suggests are ten times more susceptible to erosion than mineral soils (Evans, 1992). Thomas (1965) showed that sheep scars were initiated at summer grazing densities of 0.2 – 0.4 ha per sheep on slopes of between 15° and 25° on a good grassy sward on mineral soils. Severe erosion is most likely on slopes greater than 15° (Evans, pers. comm.). Other slopes, with their associated vegetation types, may be more susceptible to erosion although less palatable grasses may mean that these areas are less heavily grazed (Evans, 1997). Grant *et al* (1985) found that 0.4ha per sheep were sufficient to initiate heather decline on blanket bog. They also observed that over a period of eight years 0.7 ha per sheep was also sufficient to maintain a decline in heather. It has been commented that the reduced length of grassy swards as a result of sheep grazing has increased the area of grazing suitable for rabbits. This combination has been responsible for large areas of bare ground in upper Teesdale (Evans, 1997). Increasing numbers of grazing animals put greater pressure on land and often pasture is grazed in winter when vegetation is dormant. The increasing practice of over-wintering sheep on the fells (due to a lack of suitable lowland grazing) combined with a decline in shepherding (whereby sheep are moved regularly) has major implications for grassland recovery. Winter grazing of pastures in the eastern US has been shown to lead to an 8% increase in winter runoff and an even greater increase in sediment yield because up to 60% of soil loss occurs in winter (Owens *et al*, 1997).

Since the second world war the number of sheep grazing the fells of the British Isles has risen markedly. Sheep subsidies were first introduced in 1947 although in some areas flocks were not dramatically increased until the UK joined the European Community in 1973. Grazing statistics for the Lune catchment are discussed in the following section.

3.1.4 Stocking density in the Lune catchment

Farm-based agricultural statistics have been collected by the Board of Trade for England and Wales since 1866 and preserved in the form of parish summaries. These summaries contain information about numbers of livestock (sheep, cattle, pigs, horses) and acreage of crops and grassland and are kept at the public records office in Kew, London. Prior to 1917 statistics were collected on a voluntary basis, and hence it may be assumed that there is greater accuracy in the agricultural returns after 1917 when it became compulsory to make returns. The statistics used in this study extend from 1866 to 1988 after which time records have yet to be released. Forty one parishes are contained approximately within the Lune catchment and cumulative totals of statistics for all of the parishes are shown Figure 3.4. The acreage of grassland has changed very little over time although more rough pasture has been converted to improved grassland. The number of cattle rose to a peak of 71 000 in 1976 but has declined since. However the number of sheep has been continuing to rise approaching 500 000 in 1988. The acreage of crops, although increasing during the second world war to about 8000 ha (approximately 8% of the catchment area), accounts for a very small proportion in the catchment (230 ha in 1988, Figure 3.5).

Figure 3.4 Agricultural statistics for Lune catchment

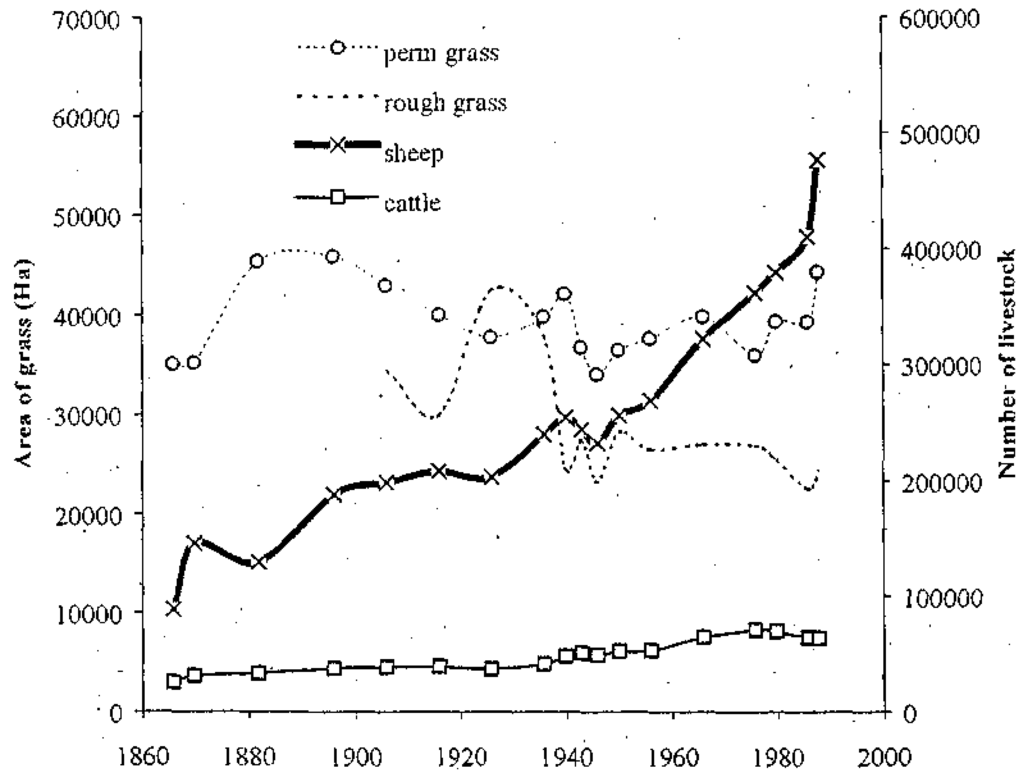
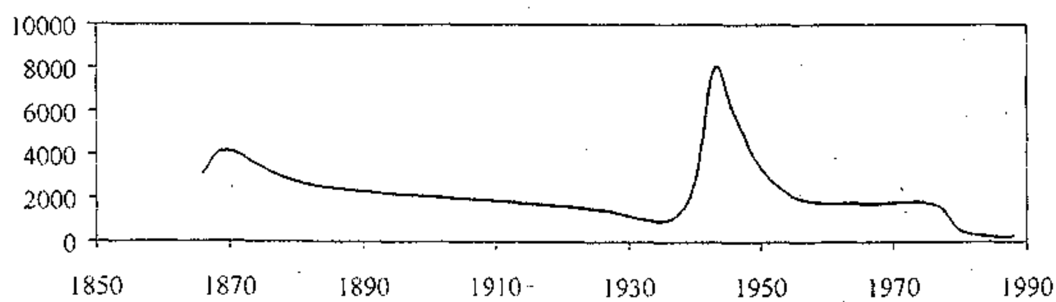


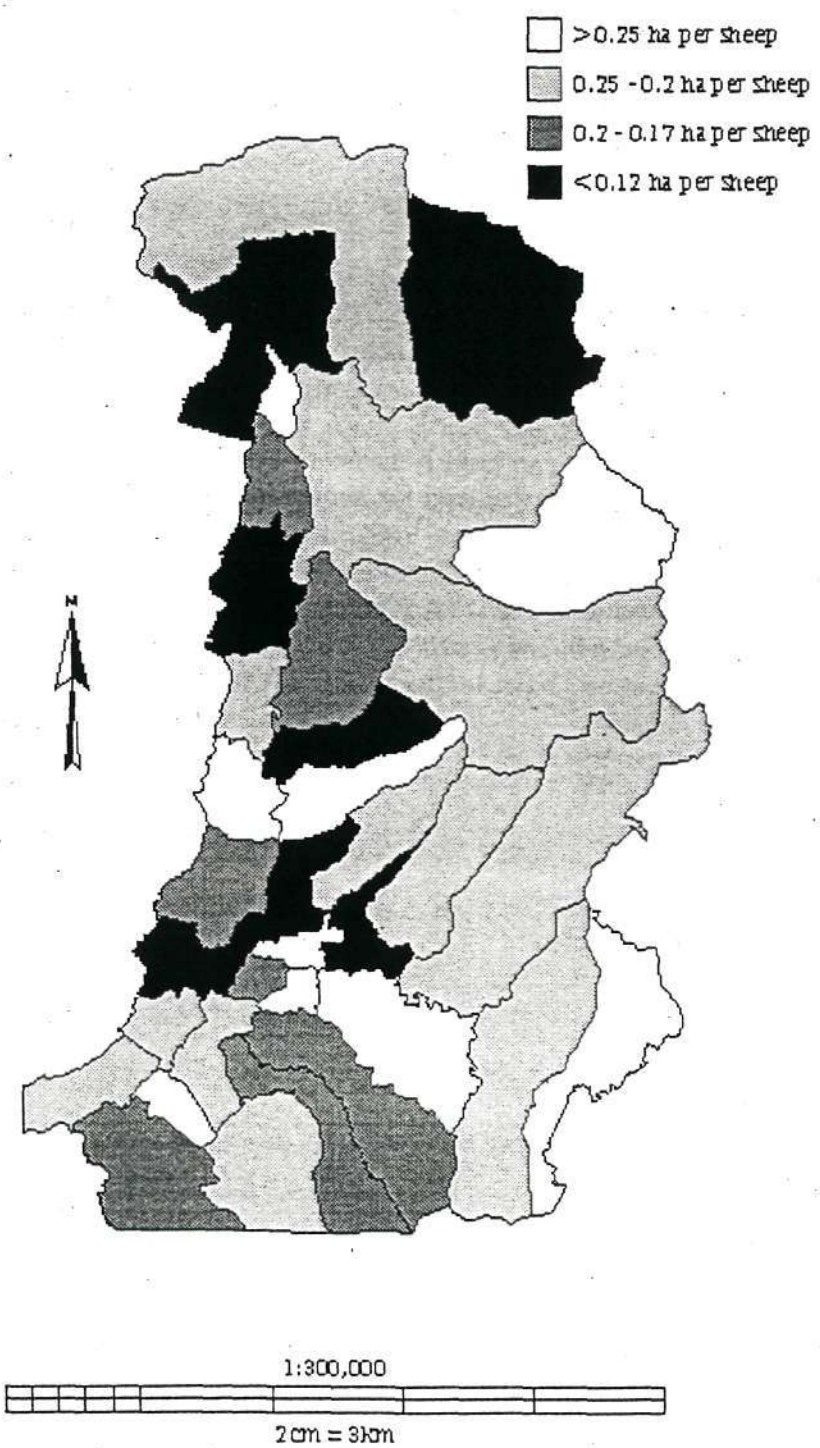
Figure 3.5 Spatial extent of cropland (Ha)



The grazing density for sheep in each of the parishes within the catchment is shown in Figure 3.6. Throughout the upland areas of the catchment (>300 m) there are less than 0.25 ha per sheep and in many cases less than 0.15 ha per sheep. Although these figures apply to all the land in the parish, it should be noted that not all land is available for grazing and in many locations these density figures represent a minimum. Much of the grazing land available has been improved over time and some more lowland areas may be able to support greater numbers of sheep. However studies from other parts of the Britain indicate that Lune catchment grazing densities are comparatively high.

Sheep have a tendency to migrate to higher ground to sleep at night, sheltering in any overhang and rubbing to create small hollows; this activity results in what are called sheep scars or scrapes. Sheep scars are usually characterised by bare soil with small up-slope cliffs as shown in Figure 3.7

Figure 3.6 Sheep grazing density by parish in 1988



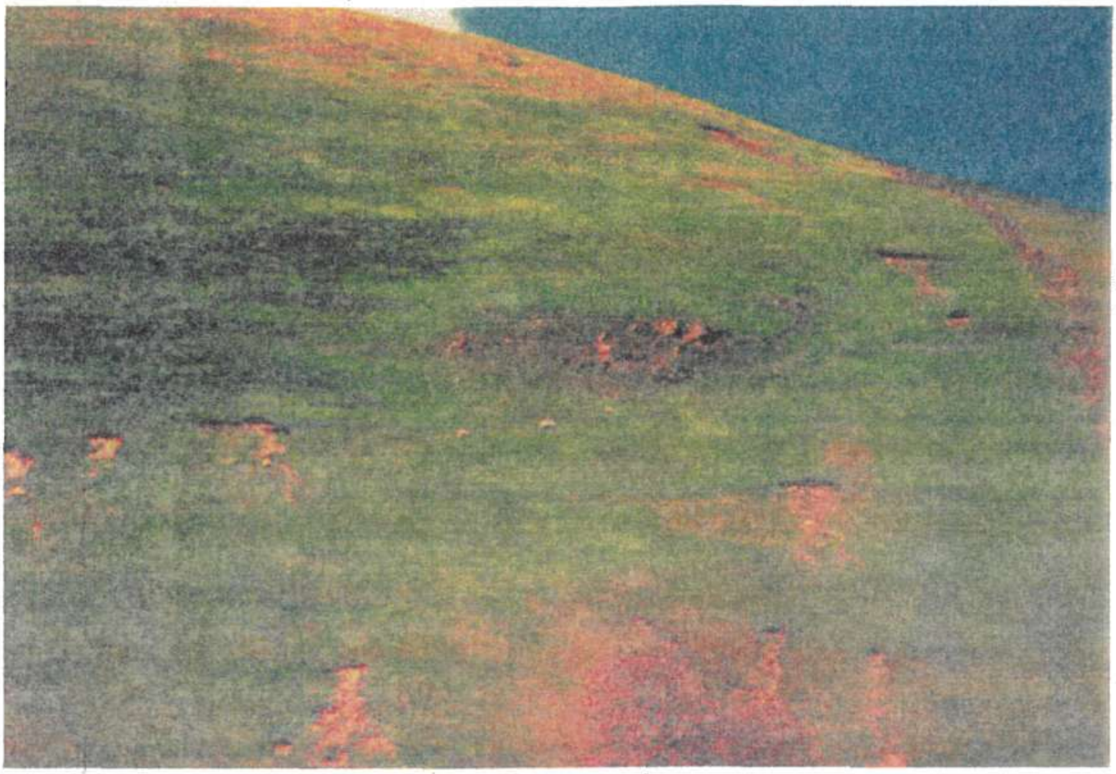


Figure 3.7 Sheep scars, Barbondale, Lune catchment

Sheep scars on steep slopes are particularly prone to erosion and produce down-slope accumulations of sediment that can extend for hundreds of meters. If erosion is acute, gullies can begin to form. Once gullies have formed it is difficult to identify the original source of the erosion, since these gullies resemble natural erosion features as shown in Figure 3.8. Barbondale feeds into the river Lune from the east and exhibits some of the more obvious and acute erosion within the catchment. Many of these sheep-induced erosion features have merged to produce growing scree deposits (see figure 3.9 and 3.10). Figures 3.7 to 3.10 are all from Barbondale (Lune catchment), which had a grazing density of 0.14 ha per sheep (7 sheep per hectare) in 1988; the approximate slope angle is 30°.

Figure 3.8 Gully development from sheep scars

Figure 3.9 Sheep scars and scree formation

Figure 3.10 Sheep scars and scree formation

In 1992/3 MAFF introduced the Environmentally Sensitive Area scheme (ESA) to encourage stocking levels not exceeding 1.5 ewes per hectare (minimum of 0.3 ha per sheep). The ESA scheme has not been widely adopted and grazing densities remain higher throughout much of Britain. However relevant Institutional bodies (MAFF, National Farmers Union, Environment Agency) are becoming increasingly aware of the potential problems of overgrazing in terms of erosion, sediment pollution and changing runoff. It is likely that the policy of upland sheep subsidies, which constitute the main income for hill sheep, will, at some point be revised. Alternative methods for upland management include reducing stock, introducing effective shepherding (moving stock off some areas), fencing and alternative sources of income (e.g. tourism). Milne (1996) suggests that a range of grazing densities is required to sustain our natural heritage and that integrated management is required to deliver environmental benefits. Even in quite severely degraded soils, soil stabilisation can be observed within a few years of grazing exclusion (Greenwood *et al*, 1998) combined with rapid improvements in vegetation cover (Hope *et al*, 1996).

3.1.5 Impacts of vegetation loss from riparian zones

Changing farming practices over hundreds of years have been responsible for the loss of floodplain forests and riparian zone vegetation. Riverside trees have been removed and not replaced partly as a result of changing management practices and because of grazing pressure. Bank vegetation reduces the energy of the flow close to the banks by reducing shear stress; protection is then afforded to the banks. Old floodplain maps of the Lune and anecdotal evidence suggest extensive loss of riparian trees from the main floodplain. During the 1970s and 1980s isolated trees were often removed from the riverbanks as they were often perceived to create an erosion risk and large woody debris can cause damage to bridges and create obstructions to flow. Larger isolated trees on the bank can cause concentrations of turbulent energy in their wakes and lead to scour immediately downstream; the location of trees on the bank profile and the longitudinal spacing determines their geomorphological effectiveness. However of most concern to present day management of riparian zones is the effect of livestock grazing on riparian vegetation. Heavy grazing in riparian areas produces banks vegetated by close-cropped grass with either steeply eroding cliffs or composite profiles (definitions are as described in the Environment Agency's River Habitat Survey Manual). The direct effects of livestock grazing in riparian zones have been summarised as follows by Harper *et al* (1998):

- Higher stream temperatures from lack of sufficient woody streamside cover.
- Excessive sediment in the channel from bank erosion.
- Channel widening from hoof-caused bank sloughing and later erosion by water.
- Change, reduction or elimination of vegetation.
- Elimination of riparian areas by channel degradation and lowering of the water table.
- Gradual stream trenching or braiding depending on soils and substrate composition with concurrent replacement of riparian vegetation with more xeric plant species.

There is considerable literature on the effects of riparian vegetation loss on bank stability (Thorne, 1990; Williamson, 1992). In Britain research largely relates to accelerated rates of bank erosion without specific discussion of impacts by livestock. Rangeland research in America (e.g. Trimble and Mendel, 1995) and New Zealand is a major source of information. However it is difficult to separate scientific research from opinion as identified in a review of the American literature by Kauffman and Kreuger (1995). Literature from the ecological community relates largely to the role of vegetation particularly for fish habitat requirements (Campbell and Maitland, 1996; Harper *et al*, 1988; O'Grady, 1993). It is generally accepted that overgrazed riverbanks are detrimental to riparian ecosystems and the stability of channel morphology. Most of the research effort relating to riparian zones and livestock has been aimed at stream rehabilitation without a clear understanding of the processes operating; as a result, many of the reported cases give contradictory results. The literature highlights the need to consider the effects of livestock in the context of all land use activity, past and present and the physical state of the river system in question.

The width-depth ratio of some American rivers has been increasing due to accelerated streambank erosion (Rosgen, 1996). This is often the most obvious visual impact of overgrazing and one of particular interest for flood defence. It is known that riffle spacing is closely related to channel width. If channel width is destabilised, as a result of bank erosion, then major rearrangement of the bed can occur, enhancing the impression of sediment related problems (Thorne, 1990; Thorne *et al*, 1992). EA Flood Defence has identified this as an issue in the River Lune.

It is difficult to predict rates of erosion from levels of grazing and the available literature is very site specific. Work in New Zealand suggested that grazing alone was not enough to cause accelerated bank erosion (except in streams <2 m wide) unless channelisation had taken place. But once accelerated erosion had been initiated, removal of stock alone was not enough to stabilise banks in streams with widths greater than 15 m; tree planting would also be required (Williamson *et al*, 1992). It has been noted that to stop grazing completely may not be the ideal solution to erosion problems and that a degree of grazing may be necessary to maintain an appropriate vegetative mix (Sýkora *et al*, 1990). Removal of grazing animals can lead to the invasion of pest vegetation species which may be undesirable, for example Japanese Knotweed (Beerling, 1991).

There is a need for research, which defines the hydroclimatological, edaphic and geomorphological dimensions of study areas in order that the controlling variables in accelerated bank erosion may be more clearly defined (Trimble and Mendel, 1995). There is also a requirement for monitoring and a clear understanding of the processes involved in re-vegetation following grazing restrictions and fencing. O'Grady (1993) reported a significant decline in juvenile salmonids in channels that had overhanging riparian vegetation during the summer compared with adjacent open sites. However it would appear that the result was most significant for channels referred to in the fluvial geomorphic literature as enclosed and overgrown drainage ditches of narrow width (1.6 to 8.5 m). Such impacts may not be the case in more natural channels or those that are carefully rehabilitated. A review of the fisheries literature (O'Grady, 1993) shows that bankside vegetation plays a complex and variable ecological role.

3.1.6 Vegetation change in the Lune catchment

Evidence of vegetation change for the area is all anecdotal, vegetative surveys have concentrated on the nearby Lake District. There have been no major vegetation surveys within the Lune catchment. Halliday (pers. comm.) describes the Howgill Fells as a matt grass desert with a few sheep resistant hawthorns. Matt grass (*Nardus stricta*) is one of the least palatable grasses. The Institute of Terrestrial Ecology's land classification system covers the area at a coarse scale but there are no known comparative temporal studies. Local mycologist Dr Juliet Frankland has expressed concern about the Howgill Fells and the decline in species diversity, particularly with regard to the management of the common land, which accounts for most of the area. Most of the rough grazing in the Howgill Fells is common land (effectively the area above 300 m). There is no management of the commons in terms of grazing control and the Commons Registration Act did nothing substantially to change this. In principle there are historical rights to grazing for individual farms or parishes. Considerable anecdotal information describes vegetation changes. Farms that are managed in the traditional way, where sheep are adequately catered for on inbye land (lowland pasture) over winter and shepherded on the fells, still have wild flower meadows. The headage payments and uncontrolled common grazing have meant that many farms have increased their stock and no longer have sufficient inbye land for winter grazing consequently sheep over-winter on the fell. In the late 1930s Blackforce screes (in Carlingill) on the west side of the Howgills were covered in dense heather, sixty years later they are just bare rock (Frankland, pers. comm.). The fell tops would have been heather covered sixty years ago but thick heather stands previously on lower land are now scarce. Dense stands of bracken can be observed up to 400 m and cover entire hillsides e.g. Brown Moor (GR SD36454966). An exploratory and largely qualitative vegetation survey of the Calf Beck valley (GR NY 366000, 496600, approximately 2 km^2) and adjacent fells found one small area of billberry (10 m^2), some small clumps of Juncus rush and elsewhere close cropped matt grass. It should also be noted that this valley system was littered with sheep scars which, in some cases, appear to have developed into active gullies. Most of the lower slopes of the Howgill are littered with alluvial fans and debris cones both active and relict and gully systems have always been evident (Harvey, 1985, see his Figure

7.3). However the Calf Valley is showing signs of recent gully development. Field evidence points towards sheep grazing as the cause (see Figure 3.11).

Figure 3.11 Gully development from sheep scars

Using the evidence from Barbondale where erosion was occurring on slopes greater than 30° an erosion risk map was constructed using the functions within ARCINFO on the Geographic Information system. The resulting map is shown in Figure 3.12 and clearly shows the Barbondale slopes and most of the valleys in the Howgill Fells, to be at risk from erosion. These areas also correspond to high levels of grazing density.

There are other indicators of change; since 1993 an increasing distribution of the aquatic macrophyte, ranunculus has been observed in the upper Lune above Tebay (Mycock, EA, pers. comm.). This plant cannot survive in fast flowing rivers and it has never before been observed in the Lune. The only location free of it is the fast flowing channelised section upstream of Kelleth (GR NY366000, 505000). The summer of 1998 saw a plague of antler moth caterpillars in the Howgill Fells. More than 16 000 ha of grazing land was affected and sheep had to move down to lower pastures adding pressure to those areas (Sansom, 1998). Population explosions of these moths have occurred in the past and vegetation has recovered but, like all ecological explosions and extreme natural phenomena, unsympathetic land management may upset the balance.

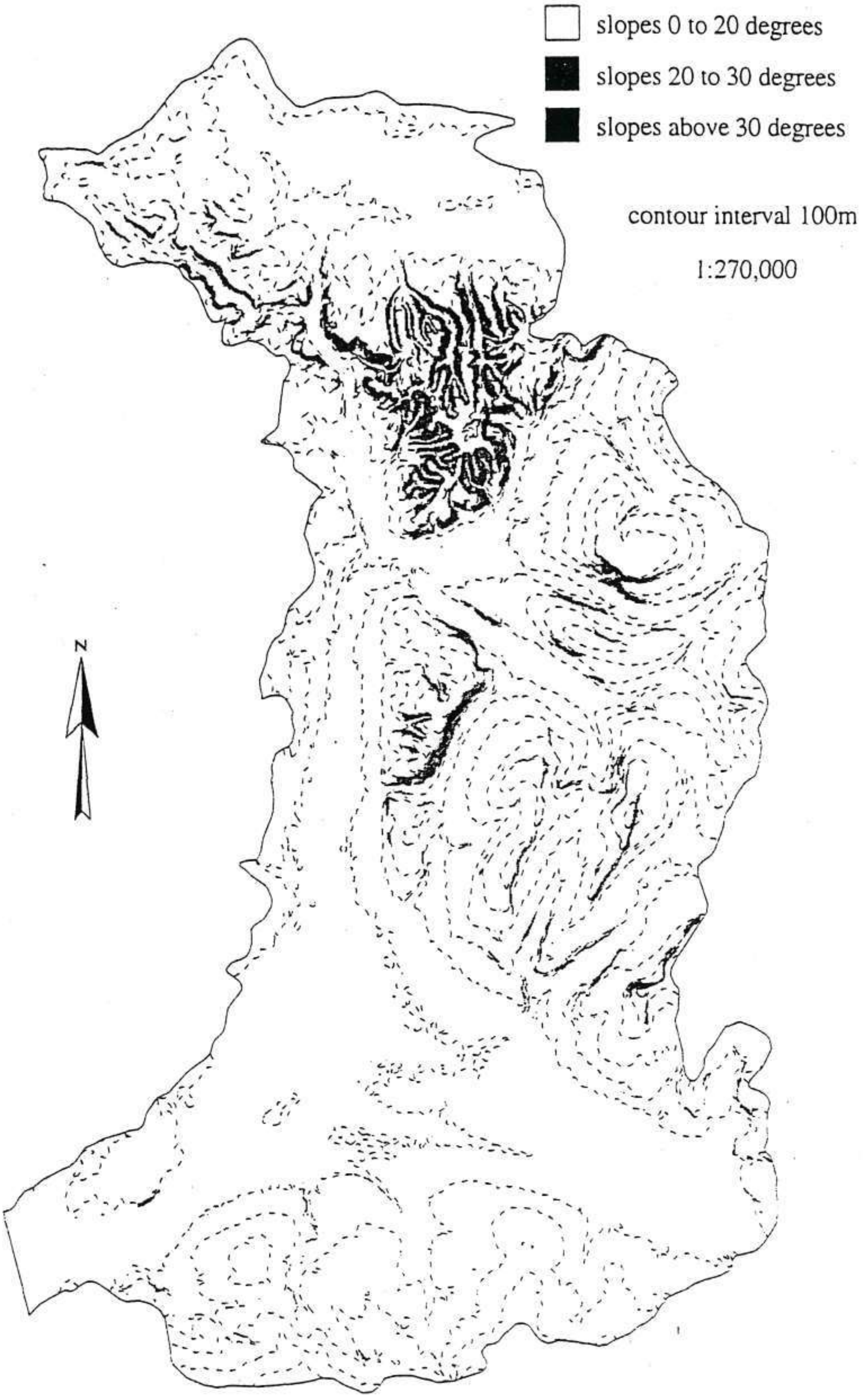


Figure 3.12 Slopes at risk from erosion

There is no quantitative evidence of riparian vegetation change, although it is known that the Lancashire River Board conducted a riparian tree clearance initiative. This was in part a response to damage in the village of Wray, in 1967, caused by intense rainfall which resulted in a wave of floodwater ripping out trees and causing significant damage to buildings in the village (Duckworth and Seed, 1969). The trees and woody debris carried by the floodwater were thought to have caused much of the damage to bridges and buildings. Today the majority of the banks on the main river floodplain are close-cropped grass with isolated clumps of trees; very few areas are fenced to protect vegetation from the effects of livestock grazing. Extensive grazing and trampling effects over long time periods has lead to vegetation loss on river banks throughout the main floodplain between Kirkby Lonsdale and Caton. Isolated stands of Japanese Knotweed can be found at a number of locations (e.g. Lune gorge, River Wenning). Parts of the upper Lune in the Lune gorge have bracken as the major riparian vegetation. Old maps of the area show extensive damp areas "liable to flooding"; there is very little evidence today, in the field, of wetland vegetation or wetland areas. Two notable exceptions are at Arkholme (GR 590720), an island backwater and The Snab (GR 562679), an old meander channel used at high flow but containing water most of the year.

3.2 LAND DRAINAGE CHANGES

The primary objective of land drainage is the development of fertile land for agricultural production. Early records of land drainage in Britain date back 2000 years (Brookes, 1988). Flood control and agricultural drainage schemes have been carried out by different organisations for 550 years. Some legislation has been significant, the Statute of Sewers in 1427 and the Court of Sewers Act in 1531 which compelled riparian landowners to maintain adjacent channels (Brookes, 1988). The Land Drainage Act of 1861 hailed the adoption of modern field drainage in Britain, but only in recent years has the total annual amount of underdrainage equalled that of the mid nineteenth century. The 1861 Act allowed the improvement and maintenance of existing works and also the construction of new works. There was thought to be little drainage between 1880 and 1940 but countrywide statistics only began in 1940. It is estimated that 60% of agricultural land in north west England has been subject to field underdrainage, the pace of drainage accelerated in the late 1960s (Green, 1980). Moor drainage is believed to have been practised for the last 150 years (Stewart and Lance, 1983)

3.2.1 Field drains, arterial drainage and moor gripping

Drainage activities can be divided into three main types, underground field drains, open ditches and channel modifications or channelisation. Field drains ensure a suitable environment for crop root development and can range from the development of covered ditches to pipe and mole systems. Bailey and Bree (1981) examined the effects of land drainage on river flood flows by looking at pre and post drainage records on twelve catchments in Ireland. The general conclusions from this study are summarised below:

- Drainage works cause an increase in flood peaks.
- The unit hydrograph time to peak is significantly reduced, while the peak ordinate is increased.

- Effective field drainage modifies the natural water regime of soils, particularly in providing a storage function for subsequent precipitation by increasing infiltration relative to surface runoff.
- In the case of field drainage works for control of rising groundwater, the effect is to reduce flood peaks.
- The major cause in the increase of flood peaks is channel 'improvement' itself and not the modification of soil water by field drainage.

The exact impact of agricultural drainage on river flow is difficult to assess because runoff is dependent on many external drivers e.g. rainfall intensity and antecedent soil moisture conditions. Newson and Robinson (1983) found that upland field drainage reduced downstream peak discharges but they stressed that different conclusions could be drawn in other systems and the study did not incorporate any major floods that may exceed certain system thresholds. A review of the hydrological impact of land drainage in the USA by Skaggs *et al* (1994) concluded that in most circumstances land drainage results in increased peak runoff, sediment and nutrient losses from soils. Konyha *et al* (1992) showed that the magnitude of peak runoff depends on the size of the catchment, characteristics of the river channels and the location of the outlet and the area of drainage. They demonstrated that the channel network may dampen a 400% increase in peak flow at a field boundary so that the increase at the river catchment outlet is in the order of 10 to 50%. Skaggs *et al* (1994) concluded from their review that field underdrainage systems had less surface runoff and lower peak outflow rates than undrained fields, which is in agreement with Bailey and Bree (1981).

Robinson (1990) has undertaken a comprehensive review of land drainage impacts in the Britain. This report highlights the lack of information on the effects of drainage at the large catchment scale. Earlier reviews (Rycroft and Massey, 1975 and Bailey and Bree, 1981) found studies, which addressed the impact of drainage on river flow, only in very small catchments (6 ha). A third important paper (Howe *et al*, 1967) found increased flood frequencies in the upper Severn but there were similar trends observed in the rainfall records for the area. The conclusion of this work was that increased numbers of storm events had triggered the increase in flooding, aggravated by the concomitant changes in land use (forestry). Part of the problem, outlined by Robinson (1990), is that field drainage effects have traditionally been studied by agricultural engineers concerned with the field scale while river flow was the domain of flood defence engineers who, until very recently, were only concerned with reach scale and not catchment scale. Some drainage records have been kept (MAFF funded drainage schemes) but these are not readily available and do not include all drainage or dates of work. Statistical records of all drainage in England and Wales were collected by the MAFF for the period 1970-1980 at the parish scale. It is estimated that during the decade 1970 – 1980 about 10% of England and Wales was drained, equivalent to the total drainage of the previous three decades. The north west was thought to have been less intensively drained (Robinson and Armstrong, 1988). Green (1979) estimated that during 1949-1976, field underdrainage affected 5-10% of the agricultural land nationally under crops and grass. Armstrong (1978) lists the drainage statistics for MAFF districts and regions; the closest area for the Lune catchment is Carlisle District, which roughly corresponds to the county of Cumbria. The statistics in Table 3.2 show the area of drainage given grant approval for that year. Many of the schemes were not later taken up but they have been shown to be representative of drainage activity.

Table 3.2 Drainage statistics for Carlisle District

Year	Total scheme area (ha)
1.4.71 – 31.3.72	995
1.4.72 – 31.3.73	1718
1.4.73 – 31.3.74	2499
1.4.74 – 31.3.75	2339
1.4.75 – 31.3.76	933
1.4.76 – 31.3.77	790
1.4.77 – 31.3.78	1516

Total drainage over 8 year period = 10790 ha

Robinson (1990) in part of his review conducted two catchment scale (17 km^2) studies examining the runoff response to rainfall where there was a known increase in land drainage. In both cases storm peak discharge had increased. The report also emphasised the importance of soil type within a catchment when considering the effects of land drainage; some of the summary conclusions of this report are listed here:

- The drainage of heavy clay soils generally results in a lowering of large and medium flow peaks. This is because the natural response is flashy with limited soil water storage available. When such catchments are drained surface saturation is largely eliminated.
- On permeable soils less prone to surface saturation, the more usual effect of drainage is to improve the speed of subsurface discharges, tending to increase peak flows.
- The likely effect of field drainage may be assessed from measurable soil characteristics.
- Modelling indicated the importance of rainfall regime: drainage reduces maximum discharges from higher rainfall areas. Baseflows were higher from drained than undrained land, principally as a result of the greater depth of the drains than the former unimproved channels.
- Studies of flow records from individual catchments indicate that the combined effect of field drainage and arterial works is to increase streamflow peaks (and dry weather flows) whether or not maximum flows are increased or decreased at the field scale.
- At the regional scale, artificial drainage is a statistically significant parameter shortening catchment response times.

Land drainage induces hydrological changes which could affect stream channel morphology; this has not been widely researched. A study of streams in Quebec (Leduc and Roy, 1990) showed that for similar drainage areas, small stream channels of watersheds with land drainage are larger in width and cross sectional area than those without land drainage.

In Britain there has been some research on the runoff effects of plantation forests. The process of forest drainage creates shorter pathways for groundwater and overland flow into river channels, which in turn changes the basic runoff processes in the catchment (Iritz *et al*, 1994). Results from studies of the effects of forest drainage are conflicting because of the range of conditions. However a study of three methods, control basin, conceptual and distributed models all showed that the effect on peak flows was greatest after dry periods. Predictions from the SHE (Système Hydrologique Européen) model indicates that the highest peak flows could be increased by drainage in cases of intensive rainstorms in catchments with already high groundwater (i.e. close to the soil surface). The general tendency of the drainage effects was that a lowered groundwater level had greater influence on peak flow formation than the incised channel conveyance capacity in the drained catchments (Iritz, 1994).

Moor draining or gripping traditionally takes the form of open ditches cut 40-50 cm deep and 15-35 m apart; drains may run along the contour or lie in a herringbone pattern. The drains are cut with the Cuthbertson plough specially designed for the purpose and drainage operations increased with its invention and the introduction of a 50% grant from the late 1940s. There are 1.5 million ha of native hill pasture in Britain (Stewart and Lance, 1983), yet there appears to be no record of the extent of moor griping or its effectiveness. The practice was 70% grant funded but there is no documentary evidence of economic benefits. Today there are grants available to block moor grips (English Nature and MAFF). Stewart and Lance (1983) conducted the only known review of this practice. They suggest that although drainage was aimed to relieve saturation this only occurs within 1-2 m of the drain edge and benefits to grazing sheep are mere surmise. Heather is an important winter fodder for sheep and it does grow taller and denser after drainage but again only immediately adjacent to drains. Alleged increases in grouse numbers are not significant against the natural population fluctuations (Newbourne and Booth, 1995). Stewart and Lance (1983) listed the drawbacks of moor draining as being: landscape scarring, downstream flooding, rush invasion (Juncus spp.), increase in liver flukes (supposed to be prevented by drainage) and sedimentation in streams important for fish and water supplies. They believed that the drawbacks of drainage outweighed the benefits. They found that moor drainage has often lead to increased stocking density in the belief that the quality of grazing had been substantially improved but this is unlikely to be the case. Following their original review Stewart and Lance (1991) studied the effects of moor drains in reducing soil moisture and confirmed the effects were limited to a few meters around the drain. They also noted that long-term vegetation changes were only observed on the downslope side of drains for a distance of a few meters.

3.2.2 River channelisation

The practice of river channelisation with a view to improving land drainage has been the subject of considerable geomorphological research since the 1960s (Brookes and Gregory, 1988). Investigation of river channel change has been concerned traditionally with natural channel metamorphosis. In recent decades emphasis has shifted to the understanding of changes as a result of engineering activities (Gregory, 1977). Channelisation covers the practices of channel enlargement, straightening, embanking and revetment and can include maintenance works. Research has shown that the damaging effects of so-called channel 'improvements' may far outweigh the benefits, particularly in the long term. We have now entered an era of river restoration (Kondolf and Downs, 1996; Sear, 1994; Brookes, 1995), the costs of which are likely to be far in excess of the anticipated agricultural benefits from river channelisation which in many cases did not materialise.

Alteration of a river's natural course will have an effect on planform, sinuosity, cross sectional form and hydraulics. In the past engineering designs have been imposed with the sole aim of improving hydraulic conveyance. In many cases the full effects of such works are not felt for some considerable time and in other cases the effects have been immediate or unnoticed. The detrimental effects of channelisation are clearly illustrated in a case study from Canada. Extensive reaches of two rivers were straightened; almost immediately the hydraulic competence of the downstream section was destroyed by aggradation and in the upper reaches 5 m of degradation was observed in a ten-year period (Parker and Andres, 1976). Incipient meandering was observed in the downstream section and upstream of the channelisation a combination of degradation and channel migration destroyed some farmland.

Engineered channels rarely imitate the natural morphology of a river. The existence of discreet morphological units e.g. riffles, pools and gravel bars define the nature of a river. The spacing of riffles and pools is believed to reflect primary fluvial processes (see Section 4). Removal of these features disrupts the natural energy balance. The Environment Agency's River Habitat Survey classifies rivers and values their habitat based on the number of such features that are present. The removal of stable bed features and the creation of a channelised reach without regard for sediment transported by the river will usually result in some instability. Most channels will attempt some form of recovery by trying to reassert a natural bed morphology. In many streams this takes the form of short riffles and pools. In most cases channel straightening will have a destabilising effect on the river system either upstream or downstream or both (Brooks, 1987, 1994).

This study is concerned with channel, bed and bank stability and the implications for flood defence but it is worth noting that unsympathetic river engineering can have a major impact on biological and ecological systems (Brookes, 1994). All drainage activities have two common effects: increased velocity within the channel due to slope increases and with flood alleviation schemes, a reduction in the number of times the floodplain is inundated, if discharge capacity of the channel is increased. This has clear implications for in-channel habitat for plants, animals, fish and floodplain ecosystems.

Research relating to channelisation works from the biological and ecological community has tended to focus on the effects of loss of riparian vegetation on aquatic habitat (e.g. O'Grady, 1993). Channelisation can lead to the loss of riparian vegetation downstream by sedimentation (Brookes, 1986) and the loss of bankside vegetation leads to increased water temperatures and loss of shade (Boon, 1976). The impacts of fine sediment infiltration and compaction in gravel bed rivers have been discussed with reference to invertebrate communities and salmonid spawning grounds (Carling, 1987, Carling and Orr, 1990). A number of studies have related land drainage activities to the decline in density and biomass of fish and invertebrates (Swales, 1980, 1982, Cowx *et al*, 1986). In natural rivers the channels are adjusted to a wide range of flows while straightened channels tend to be designed for bankfull flow only. Extensive literature from America (Barton *et al*, 1972) is heavily weighed against channelisation with results ranging from severely destructive to moderately beneficial. Research has shown that channelised rivers are more likely to suffer accelerated rates of bank erosion from overgrazing than natural channels (Williamson *et al*, 1992). A study of vegetation following channelisation using tree ring analysis suggests that it can take up to 65 years for recovery (Hupp, 1992). River channelisation generally results in a less diverse bed morphology, which has major implications for fish habitat. The loss of habitat has been suggested as being one of the most critical adverse effects of river channelisation.

3.2.3 Extent of drainage in the Lune catchment

Stewart and Lance (1983) state that the catchment of the River Lune has not been subject to moor gripping; this is not the case. Some records have been discovered for the upper two thirds of the catchment, which indicate areas where MAFF funding was approved for both field underdrainage and moor gripping. The map in Figure 3.13 (modified from Thompson, 1984), shows the location of these areas of drainage.

The nature of soil type is important when examining the hydrological response; a hydrological classification of soils was undertaken for the north of England by Edmonds *et al* (1970). This generalised classification shows the upper parts of the Lune catchment and particularly the Howgill fells to have slow infiltration rates when thoroughly wetted. They either have a layer that impedes the downward movement of water or are clay loams to silty clay loams. The minimum infiltration rate was given as 015 - 0.27 cm/h (Edmonds *et al*, 1970) and some higher rates of infiltration were given for more low-lying soils in the mid- catchment (0.79-0.96 cm/h).

Considerable channel modifications have been made on the River Lune particularly in the upper part of some tributaries. The location of, known channel re-alignments are shown in Figure 3.14, inside the boxed areas. The total length of all engineering works on the main river and the River Wenning and Leck Beck total 23.7 km, this represents 11% of the total bank length. However much of the work is concentrated on the main floodplain of the Lune between Kirkby Lonsdale and the Crook of Lune where engineering modifications account for more than 40% of the bank length.

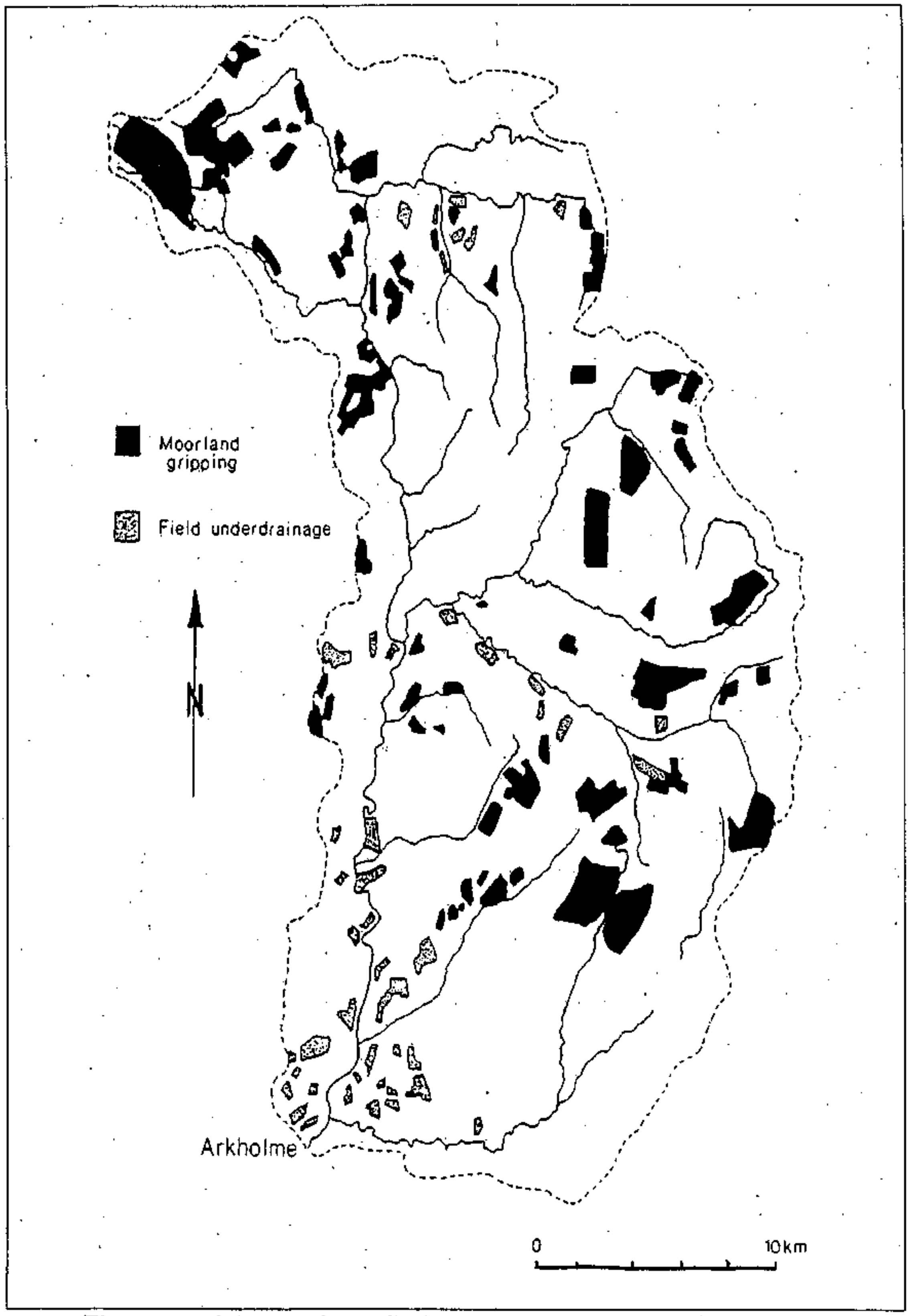


Figure 3.13 Moorland and field drainage since 1940

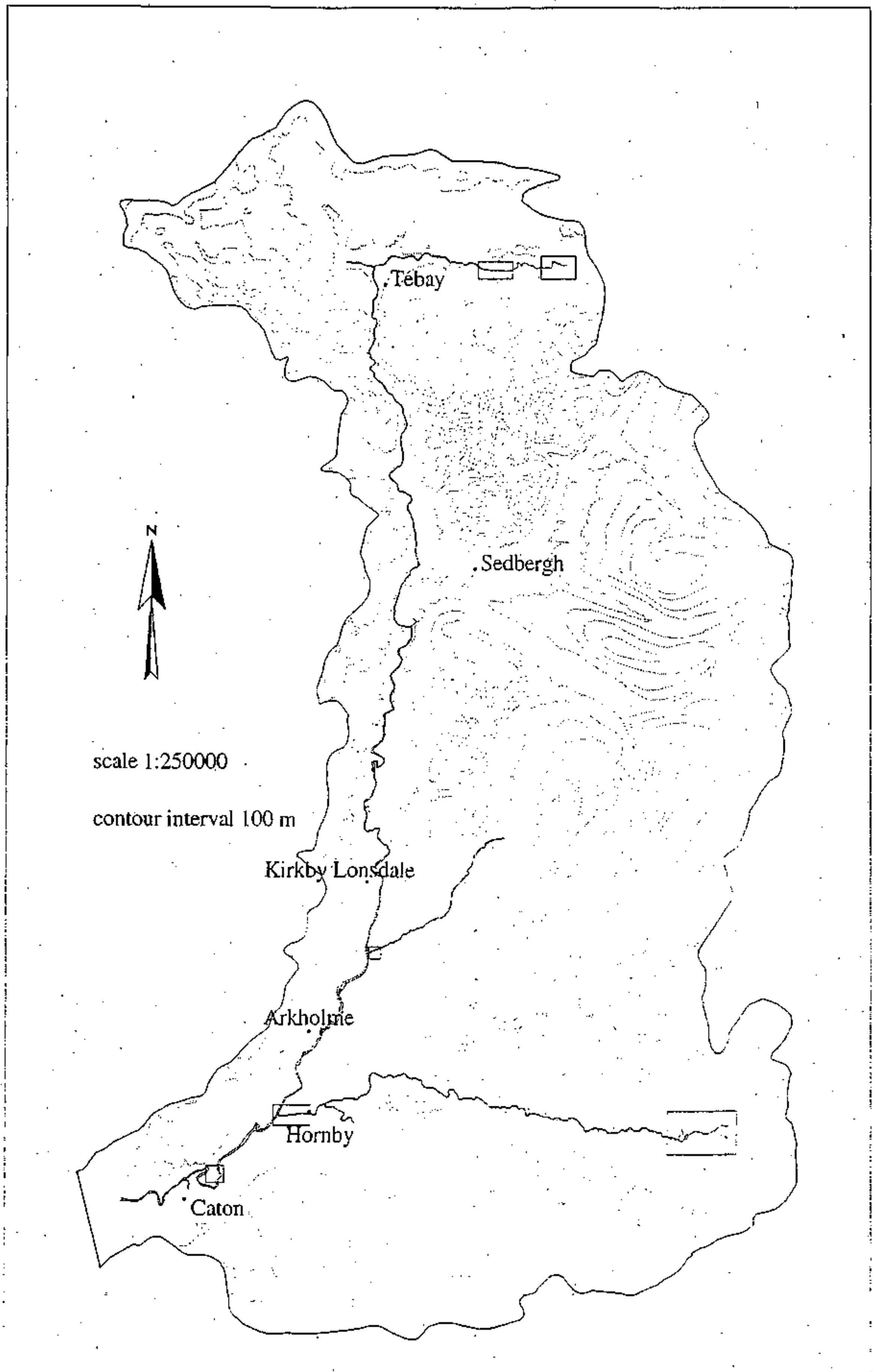


Figure 3.14 Distribution of channel realignment

3.3 DISCUSSION

After the last glaciation in Britain ended about twelve thousand years ago vegetation changes were mainly the result of climatic conditions. Man's influence began to be felt about six thousand years ago and clearance of woodland was completed over the next four thousand years. The rate of change in the countryside increased dramatically after the industrial revolution and gained further momentum after the second world war. The need to feed the nation intensified farming in Britain during the 1940s and 1950s, the same attitude led to support for hill-sheep farming in the form of headage payments (1947 to present) and grants for land drainage (1940-1970). The last decades have seen some change in the support for "farming at all costs". The environmental movement has helped to focus attention on the unsustainable nature of modern farming and there is considerable public support for conservation. The farming community is less certain of continuing support in the future hence the 1998 campaign to "Keep Britain Farming".

Concepts of "sustainability" have been expounded by government and adopted by institutions e.g. the Environment Agency. In 1998 MAFF have expressed interest in funding research into the impacts of land use. The chemical and organic pollution resulting from intensive farming has long been recognised and policed but the effects of changing vegetation as a result of intensive farming have largely been ignored. Part of the problem stems from sediment not being identified as a pollutant. The effects of fine sediment on fish habitat has been a focus of work particularly in the southern chalk streams where the fisheries have considerable monetary value in terms of licence fees. Sediment sources have largely been identified as coming from eroding riverbanks and runoff from arable land or urban areas. Sediment pollution from upland areas has not been addressed either by institutions or the research community. How long sediment from upland areas will take to reach main rivers in sufficient quantities to change the sediment dynamics is not well understood.

This chapter has identified that 150 years of upland sheep farming and twenty five years of very intensive grazing is having a marked effect on vegetation and soil erosion in upland areas. Figures 3.15 and 3.16 are computer simulations of the change in vegetation associated with different levels of grazing. The upper Lune catchment in the Howgill fells bears a close resemblance to the vegetation shown in Figure 3.15.

In the past land drainage has been blamed for perceived changes in river hydrology but the conclusions from land drainage research are varied and largely dependent on catchment characteristics (Robinson, 1980). Undoubtedly land drainage impacts on river flows but the intensive drainage activity of the past has been slowed (MAFF stopped funding schemes in 1981) whereas grazing activity continues at an intensive level. If it can be shown that current and past land use activity is having a detrimental effect on river systems particularly for those draining upland areas, the implications for one-third of Britain are serious. If it can be shown that these upland "effects" are transferred to lowland areas, e.g. by way of fine sediment pollution and changes in runoff characteristics, the implications may be more widespread.

Figure 3.15 Landscape with grazing levels at the higher end of current practice. There is little heather or scrub and evidence of erosion on steep hillsides (from Bullock, 1995).

Figure 3.16 Landscape resulting from removal of some stock resulting in regenerating of heather, trees and scrub (from Bullock, 1995)

3.4 Summary

There is substantial qualitative evidence that vegetation in the upper parts of the catchment has changed markedly. The loss of heather and billberry, broom and other similar scrubby vegetation has led to an increase in the area of less nutritious swards particularly bracken and matt grass. These vegetation changes are known to produce reduced interception rates and the subsequent heavy grazing of the resultant grass cover can lead to soil compaction and hence reduced infiltration. All the indicators are that this level of grazing will lead to increased and more rapid runoff.

The upland areas are also more likely to be eroded if the vegetation cover is reduced. Harvey (pers. comm.) suggests that the Howgill Fells have become relatively stable since the late 1960s in terms of gully erosion, he attributes this to the reduced number of summer storms. The impact of the reported changes in vegetation on fine sediment production are not known, however if runoff is increased it is highly likely that increased amounts of fine sediment are reaching river channels.

There has undoubtedly been a loss of riparian vegetation as a result of grazing pressure leading to active and extensive erosion of river banks at many locations. Past management has involved the removal of riparian trees in some locations. New trees and shrubs are unable to become established, as a result banks are weakened and erode. Channels are becoming wider and shallower in some locations as a result.

Grazing intensity within the Lune catchment has risen dramatically. Evidence from other parts of the UK suggests that the stocking densities from 1988 are high enough to cause erosion and sediment related problems. At present bare soil is visible throughout upland parts of the catchment indicating that the carrying capacity of the land has been exceeded. Farmers may not feel immediate and direct economic effects. However, if this state continues and soil is eroded to the extent that vegetation is unable to recover, the longer term impacts of erosion will be severe (Evans, 1998).

Despite being a rural catchment with approximately 40% of upland the River Lune is *perhaps surprisingly heavily managed. Although the previously high levels of channel* management in terms of channelisation have been reduced there remains an extensive inheritance of engineered channels. Evidence from other parts of the UK suggests that the extent of field drainage, moor gripping and river channelisation within the Lune catchment is likely to have noticeable impacts on catchment runoff and channel stability.

SECTION 4 DISCHARGE REGIME AND FLOOD FREQUENCY

4.0 INTRODUCTION AND OBJECTIVES

The UK is increasingly facing resource problems as a result of low flows and reduced groundwater storage. The problems in part stem from rising demand, but in the last decade there is evidence that changes in rainfall and river basin storage are important. Recent floods (e.g. Easter floods, 1998) have fuelled the debate about possible increases in flood frequency associated with climate change and land use practices and the response of water managers (e.g. Smith and Bennet, 1994). Anecdotal evidence suggests that the River Lune is becoming wider and shallower, floods are more frequent as are summer low flows and the duration of floods is reduced. Local farmers who have lived in the area all their lives, comment on the fact that large floods would keep the river close to bankfull for a week, now the river rises and falls over night. Land drainage activity has generally been held responsible for this change.

This section describes the theory of flow regime and the importance of hydrologic thresholds. A review of research, from different geographical locations in Britain, describes the consistent patterns of hydrological change that are emerging. Trends in flood frequency, magnitude and duration are compared with trends in rainfall, to apportion the importance of land use and climate change for changes in the hydrology of the Lune catchment.

4.1 BACKGROUND TO REGIME THEORY AND HYDROLOGICAL ADJUSTMENT

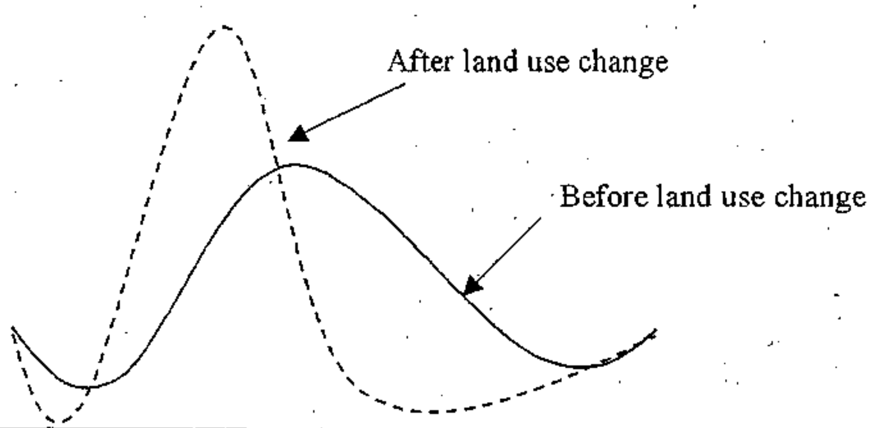
A river may be classified in some way by its regime defined by the variation of discharge through time. The discharge regime is a characterisation of the magnitude and frequency of flood events; the river Lune is one of peak winter discharges, lower summer discharges and occasional summer storm generated high flows. The catchment is highly responsive due to one third of its area being upland. In addition to long-term temporal variation in the seasonal discharge and short-term fluctuations, rivers have variability in the spatial distribution of flow, which can be non-uniform and unsteady. Non-uniformity can be observed in the changing position of the thalweg (the line of the deepest part of a channel), and changes in velocity over different bedforms (e.g. riffles and pools). Unsteadiness can be seen in the fluctuations of width and depth at a station over time either continuously or discontinuously (Allen, 1977). The degree of non-uniformity of rivers changes in response to the temporal variability of discharge. It is arguable that river channels can reach a level of stability within seasonal discharge variations, often referred to as dynamic equilibrium.

The discharge regime of a river is dictated by a number of independent variables; geology and soils, climate, vegetation (and land use), relief and hydrology (runoff and sediment yield per unit area). The two most important controls determining whether or not a channel is stable over time are sediment supply and flow regime (Werritty, 1997). If either of these undergo any change, the channel may cross, extrinsic thresholds, and change in nature. Instability can occur as a result of progressive changes in any of the independent variables which occasion drainage system response in one direction rather than about a mean (Mosley, 1975). The relationship between flow regime and sediment supply is discussed in Section 5. Extrinsic controls are those that are external to the river itself, these include climatic factors and land use changes. A river responds to a variety of these extrinsic controls, which change the flood magnitude and frequency. Flow regime may also adjust to progressive hydrological changes under the influence of human activity (primarily urbanisation and agricultural drainage). It is important to realise that the crossing of hydrologic thresholds may occur some time after the progressive change in, for example land use, which can make the identification of the cause of change or instability very difficult.

The way discharge responds to the extrinsic controls mentioned is in the size of flood peaks, the frequency of floods and their duration. There is some debate about which floods are the most geomorphologically effective, i.e. those that do the most work or produce the greatest change in river channels. It has generally been thought that the bankfull flood is the most effective but it is possible that floods that correspond to lower discharges may also be important (Werrity, 1997). Direct measurements can be made of peak discharges, which may then be compared in a time series as described in the Flood Studies Report (NERC, 1975). Flood frequency analysis is usually conducted on a "peaks over threshold" series. The flood threshold is usually chosen as that which produces, on average, two or three peaks a year. However it may be pertinent to select other thresholds, for example, the threshold for floodplain inundation.

Changes in the duration of flood events are particularly significant in terms of identifying the influences of land use. Schematic hydrographs illustrate the effect that land use changes can have on the runoff response (Figure 4.1) and the importance of different parts of the hydrograph are shown in Figure 4.2 (modified from Newson, 1996). Influences on different stages of the annual variability in the timing and volume of runoff can be represented by a simplified annual hydrograph modified from Newson (1994) and shown in Figure 4.3.

Figure 4.1 Hydrograph shape change



Traditional techniques for hydrograph analysis are problematic in terms of separating slow flow and fast flow components, the quick flow being runoff and slow flow, the contribution from through-flow. In addition, digital records for hydrographs are usually only available after 1976 when discharge gauges were automated. Rapid changes in hydrological response may be obvious in hydrograph analysis but, long-term progressive changes, often associated with land use changes, are less clear.

Beven (1991) recommends the use of statistical techniques such as the time series analysis adopted in this study. However it is possible to analyse daily discharge in terms of low flow and high flow days and measure the relative frequency of both.

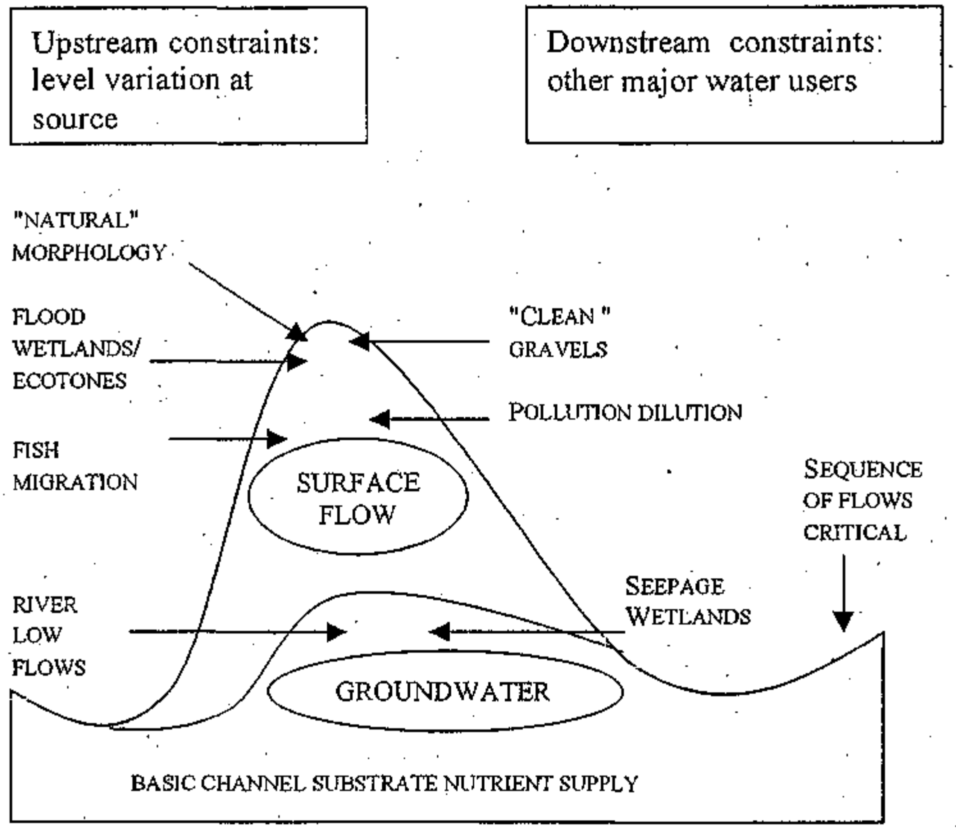
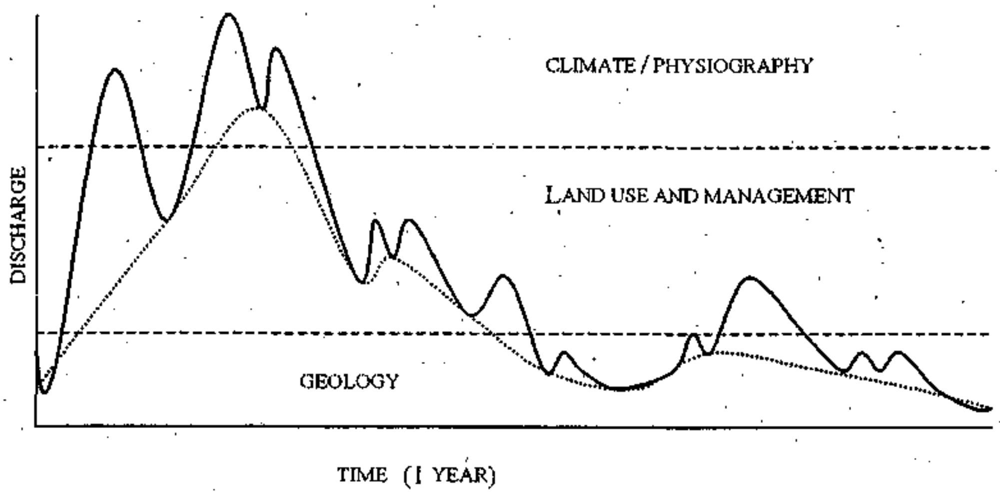


Figure 4.2 Importance of the flood hydrograph

Figure 4.3 Annual runoff cycle



Changes in the discharge regime have direct impacts on available stream power, which is defined as the ability of a river to transport sediment and cause erosion.

Stream power is a function of discharge and slope, Bull (1979) has defined the critical stream power threshold:

$$\frac{\text{Stream power (driving factors)}}{\text{Resisting power (resisting factors)}} = 1.0 \qquad \text{(Equation 4.1)}$$

The potential stream power can be defined by the stream power per unit of stream bed area (Ω), or as the work done per unit of time by the shear stress at the bed (Garcia de Jalon, 1995) shown in equation 4.2

$$\Omega = \delta.\ g.\ Q.\ J\ (\mathrm{W\ m^2}) \qquad \text{(Equation 4.2)}$$

Where δ is the density of water, g is gravity, Q is the discharge and J is the bed slope. Stream power has also been defined in similar but more specific terms in equation 4.3 (e.g. Thorne (1997), where ω_{vt} is the specific stream power, S_v is the valley slope, Q_b is bankfull discharge.

$$\omega_{vt} = 3.3\ S_v\ Q_b^{0.5} \qquad \text{(equation 4.3)}$$

A simple but important hydrological threshold is that of critical stream power, which separates periods of aggradation and degradation. Brookes (1992) reported that of 60 channels subjected to restoration work, those with stream power greater than 35 W m^2 were at greater risk of erosion and instability than those with a stream power less than 35 W m^2, however stability is in large part dependent on the sediment supply. The critical stream power threshold is discussed in detail in Section 5.1.

It should be noted that although predictions can be made of average stream power, the distribution of stream power within a channel is highly variable. The importance of topographic effects on the variation of flow fields in a channel cannot be overemphasised. Maximum shear stress follows the thalweg at low to medium flows, which in channel bends is towards the outer bank, during high flows the thalweg moves towards the centre of the channel. Other flow variation can be seen around gravel bars and over riffle pool features and in the distribution of secondary flow cells. The variation of shear stress on the bed produces the variety of different grain sizes associated with particular morphological features that in turn provide habitats for aquatic plants and animals. The ecological literature often refers to these variations as patch dynamics (e.g. Townsend, 1989).

Bedload and indeed suspended load is highly sensitive to changes in stream power, the importance of discharge in the stream power equation is illustrated by the marked increase in suspended sediment transport rates with increasing discharge. For example, in equation 4.4, suspended sediment transport rate (Gs) increases by an exponential factor of about 2.5 with increase in discharge (Q) (b is a constant) (Leopold *et al*, 1964).

$$Gs = bQ^{2.5} \qquad \text{(equation 4.4)}$$

The relationship between stream power and bedload is similar to that for suspended sediment (see Reid *et al*, 1997) however it is now well known that bedload sediment discharge is highly variable in both space and time. Stochastic bedload sediment movement is driven in part by availability and sediment supply and partly by the nature of sediment transport processes e.g. pulsing and the existence of armour layers. Suspended sediment predictions are also complicated in that most models assume that sediment and discharge fluctuations will occur in phase. Despite the difficulties associated with estimation and prediction of sediment transport the nature of the relationship between stream power and sediment discharge allows inferences to be made regarding the likely effects of increasing stream power on erosion of bed and banks. The stream power relationship becomes increasingly important for river management when not only stream power is changing as a result of climatic variability but also the resisting factors are reduced e.g. bare eroding banks from overgrazing.

Regime theory when applied to rivers, particularly in river engineering makes the assumption that a river is in dynamic equilibrium; however many rivers are not in an equilibrium state. The following quote is aimed at engineers and suggests that if enough is known, any river system may be adequately managed.

> "Regime channels tend to adjust themselves to average breadths, depths, slopes and meander sizes that depend on: the sequence of water discharges imposed on them, the sequence of sediment discharges acquired by them from catchment erosion, erosion of their own boundaries, or other sources and the liability of their cohesive banks to erosion or deposition." (Blench, 1969)

Blench's advice is accurate enough if a river is in an equilibrium state but increasingly there is evidence that many of our rivers are in a state of constant readjustment (e. g. Lewin *et al*, 1988). The rigid, and often over-simplification of regime theory, by the engineering community may explain the failure of many river works and the need for constant river maintenance. It is the variability about an average 'channel' that allows flexibility within the river system such that, for example, an increasing sediment load may be accommodated within an existing channel. Regime theory may only be applicable to short periods of time (tens of years), for the purpose of this study references to river regime assumes this timescale.

4.2 NATIONAL AND REGIONAL TRENDS

There is some evidence that serious flood frequencies have shown increases in recent decades. Howe *et al* (1966) on the Severn and Wye found the period 1911-40 to have a flood height of 5.1m every 25 years. During 1940-64 this height was reached on the Severn every 4 years with clustering of high flood events since 1930-40. The reasons for this increase are complex and probably include peat drainage in the Welsh uplands and an increase in daily rainfalls greater than 63.5mm since 1940.

Walsh *et al* (1982) showed in the Tawe valley, Swansea, of 17 major floods since 1875, 14 occurred from 1929-81 and only 3 during the 1875-1929 period. Significantly of 22 notable widespread heavy rainfalls in the Tawe since 1875 only 2 occurred from 1875-1928 but 20 from 1929-1981. However Lawler (1987) has sounded a note of caution, no simple note of synchronicity exists across the country in any changes identified but since 1968 there has in some areas been a reversal in the trend of increasing storm rainfalls and associated floods.

Rumsby and Macklin (1994) looking at climate change in NE England found episodes of widespread channel incision during the periods 1760-1799, 1875-1894 and 1955-

1969, this was as a result of a higher frequency of large floods (>20year return period) and cool wet climate under meridional circulation regimes. Phases of more moderate floods (5-20 year return period) corresponded to zonal circulation types characterised by enhanced lateral re-working and sediment transfer in upper reaches of the Tyne catchment and channel narrowing and infilling downstream (1820-1874 and 1920-1954). Rates of fluvial activity were found to be reduced in intermediate periods (1800-1819 and 1895-1919) with no dominant regime associated with lower flood frequency and magnitude.

4.3 HYDROLOGY OF THE LUNE CATCHMENT

Modern rivers in NW England developed since the retreat of the Devensian ice sheets and are of late Pleistocene/early Holocene age. Holocene river development has resulted in incision into the Pleistocene glacial and periglacial deposits, overall incision is related to long-term adjustment to Holocene water and sediment regimes. Incision during the late glacial and Holocene has not been continuous and is marked by successive terrace development. Up to three such terraces can be found on the Lune. In the upper part of the catchment, the Howgill Fells, only the low terraces date from the late prehistoric to early historic times and appear to have formed at a time of slope erosion associated with hillslope vegetation changes, man induced.

The river Lune catchment has an area of 1000 km^2 at Halton, which is just upstream of the tidal limit. The Lune changes its nature in distinct sections and the catchment area may be effectively divided into three areas with relatively distinct hydrological characteristics roughly based on divisions in the solid geology. The solid and drift geology is shown in Figures 4.4 and 4.5 (modified from the Lune LEAP) respectively, catchment divisions are shown in Figure 4.6. The Lune is a largely rural catchment and urban influences can effectively be ignored, the only significant urban conurbation is Lancaster City, which is below the tidal limit and outwith the realm of this study.

The main land use is sheep farming with some cattle farming on lower lying land. There is some grouse moorland and, with the exception of the war years, there is no significant cultivated cropping. Considerable drainage has been undertaken in the form of upland moor gripping and some field underdrainage. Although this catchment is not intensively managed in relation to many British Rivers there have been a number of engineering activities or "river improvement schemes" and considerable bank revetment work, the percentage of modified channels and banks is discussed in Section 3.

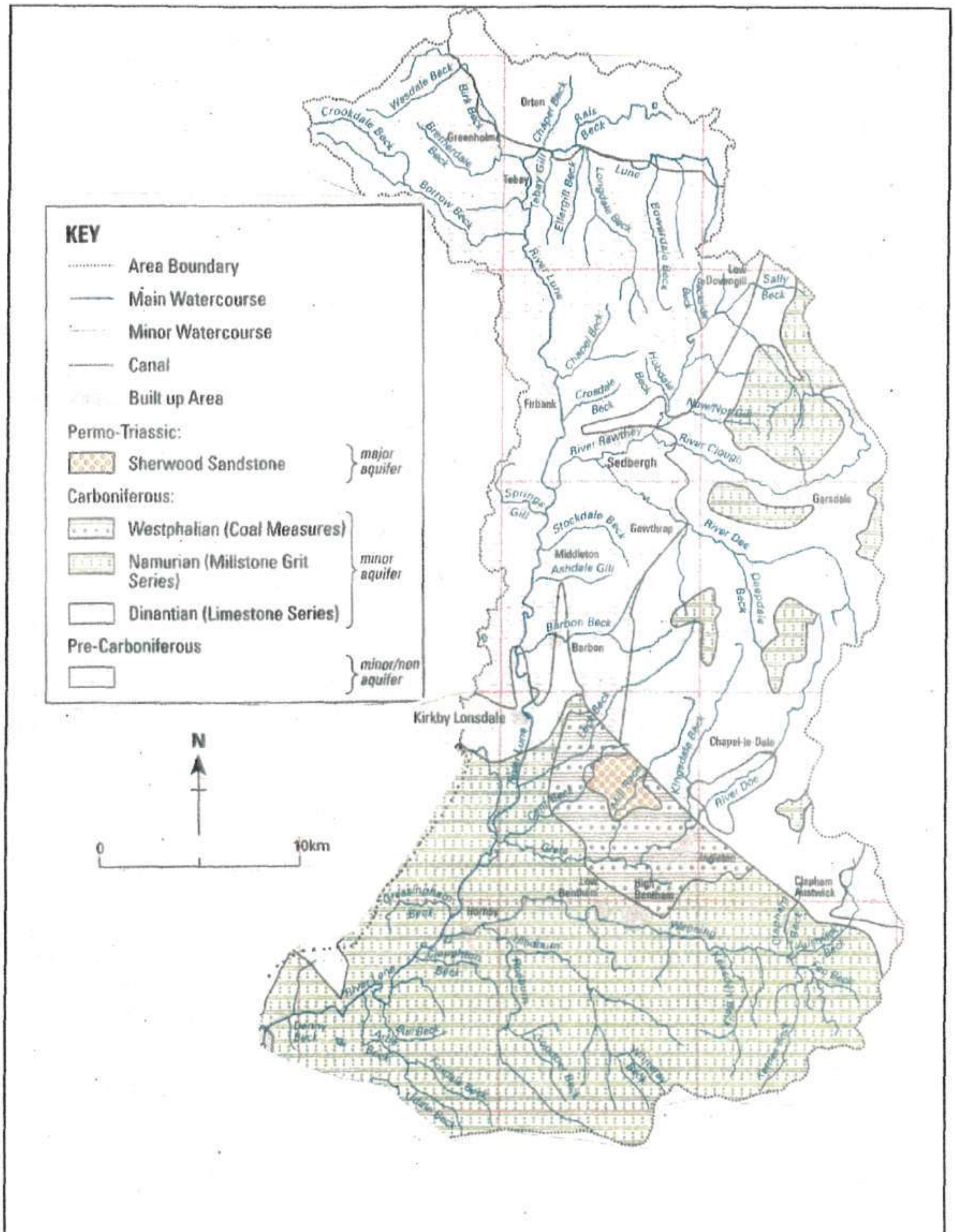


Figure 4.4 Solid Geology, Lune catchment

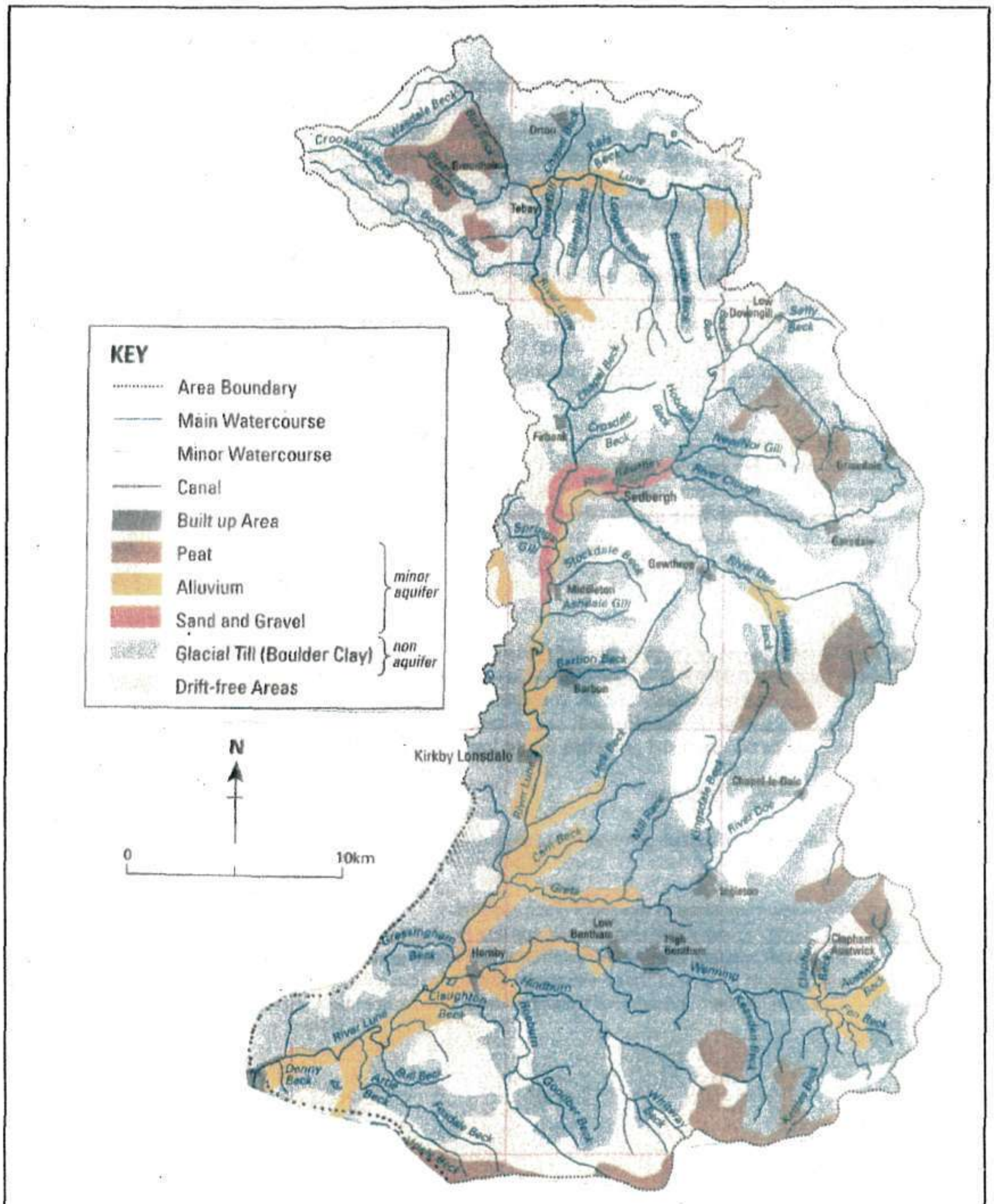


Figure 4.5 Drift Geology, Lune catchment

4.3.1 UPPER CATCHMENT

The upper Lune from the source in the Howgill Fells above Ravenstonedale flows west towards Tebay this section has a narrow floodplain. At Tebay the river turns through 90° and heads south through the Lune Gorge where the channel is confined between a succession of three terrace systems (Harvey, 1985), the lower part of this gorge is largely bedrock. The rounded Howgill fells with their steep eroding gully systems drain both to the north and to the west into the Lune and to the east into the major tributary of the Rawthey. The River Rawthey has the highest drainage density in the Lune catchment, with innumerable first order streams draining the steep slopes

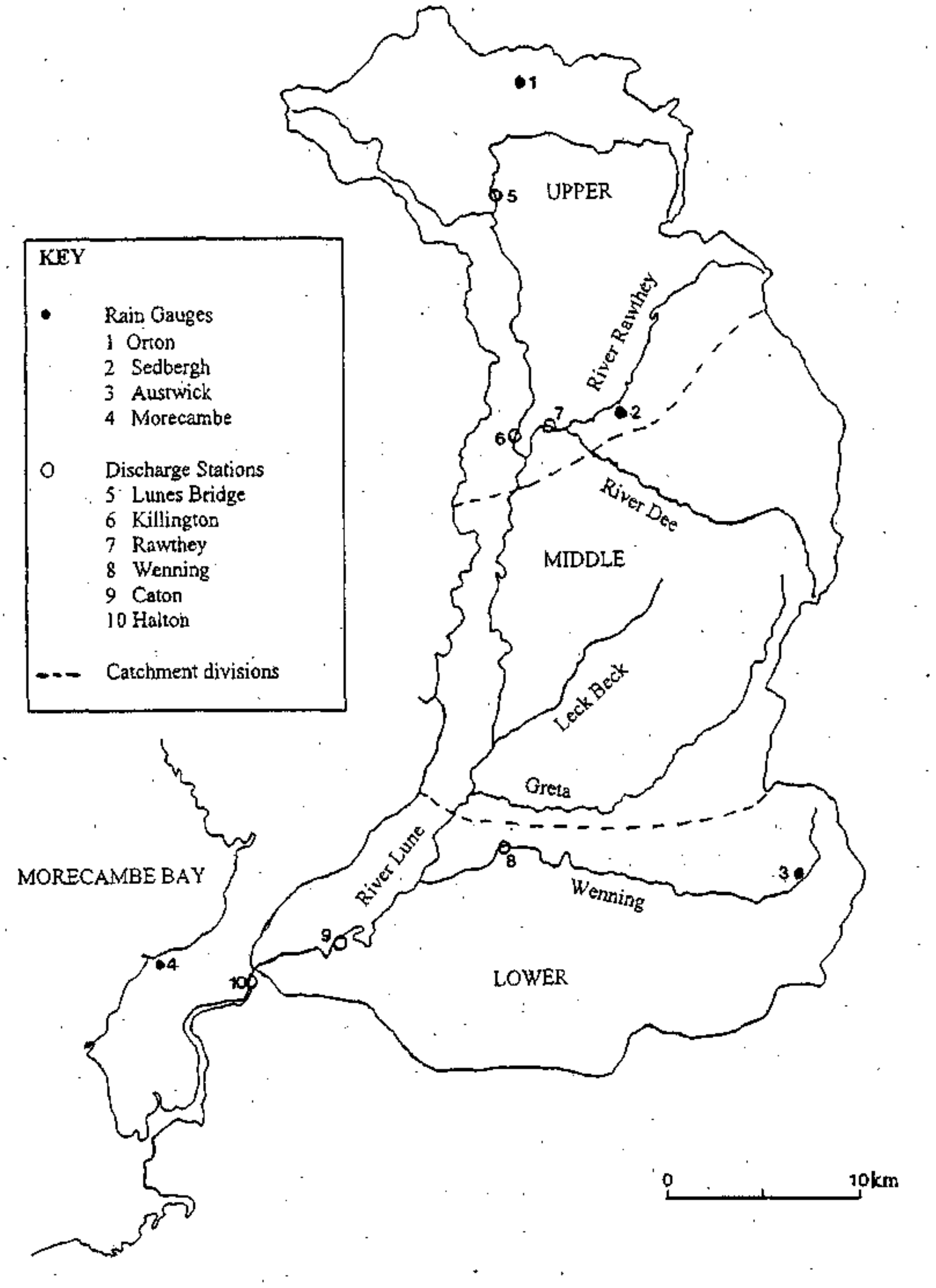


Figure 4.6 Catchment divisions

of the major valley sides. From Tebay downstream the Lune runs along the western edge of its catchment with some runoff from the eastern Shap fells into the Lune Gorge. The geology of the Howgills and the Lune Gorge is largely lower Palaeozoic pre Carboniferous and defined by the EA as a non-aquifer area (see Figures 4.4 and 4.5) the narrow floodplain north of the Howgills is situated on a band of

Carboniferous Limestone. The River Rawthey drains the Howgills and a small area of Carboniferous Limestone on the eastern edge of the catchment.

4.3.2 THE MIDDLE CATCHMENT

The middle Lune from below Kirkby Lonsdale broadens out in its floodplain, which is approximately 1 km wide. The tributaries of Leck Beck and The Greta join the Lune after draining the high peaks of Ingleborough (723m), Whernside (736m) and Crag Hill (682m). This region is composed of Carboniferous rocks, but with a more extensive outcrop of the Great Scar Limestone than in the area to the north, giving a complex network of underground drainage.

4.3.3 THE LOWER CATCHMENT

Another major tributary joins the Lune in this area. The River Wenning which drains the southern slopes of Ingleborough and the northwestern flanks of the Bowland Fells, a detached area of Millstone Grit, rising 544m OD at the head of the River Hindburn which is largely bedrock in its upper reaches. The confluence of the Wenning and The Lune marks a point at which channel activity increases and the channel becomes wider still before entering the confined bedrock gorge known as The Crook of Lune. Only one other significant tributary joins the river in this reach, Artle Beck, draining Caton Moor on the western edge of the Bowland Fells. These fells are characterised by peaty topsoil and in some areas heather and billberry still dominate, however much of the area is heavily grazed by sheep and recent open ditch drainage are thought to have affected the discharge of Artle Beck. The River Lune floodplain in this section is regularly inundated, on average once or twice a year.

4.4 HYDROLOGICAL DATA AND ANALYSIS IN THE LUNE CATCHMENT

4.4.1 GAUGED DISCHARGE DATA

The location of the rain gauges and discharge stations used in this study are shown in Figure 4.6. Several other gauges exist within the catchment but did not have sufficiently long or reliable records for analysis but have been useful in verifying data from other gauges. The details and grid references for all discharge stations are given in Table 4.3, details of rainfall gauges were given in Section 2. Some records have been combined to create a continuous record.

Table 4.3 Discharge gauging stations for the Lune catchment

Gauge	River	Name	Grid ref.	Start	End	Length
724024	Lune	Kirkby Lonsdale	SD61497776	1976	1977	2 yr.
724629	Lune	Caton	SD52866529	1977	1997	21 yr.
72803	Lune	Halton upper weir	SD51306480	1940	1962	22 yr.
72001	Lune	Halton	SD50306472	1959	1979	20 yr.
724647	Lune	Skerton Weir	SD48236334	1978	1996	19 yr.
722421	Lune	Killington	SD62209066	1976	1997	21 yr.
722242	Lune	Lunes Bridge	NY61210290	1980	1996	16 yr.
723423	Rawthey	Brigflatts	SD63999109	1976	1997	21 yr.
724326	Wenning	Wennington	SD61547008	1976	1997	21 yr.
724427	Hindburn	Wray	SD60496799	1976 *	1997	11 yr.
72807	Wenning	Hornby	SD586684	1957 #	1969	13 yr.
724528	Wenning	Hornby	SD58576837	1990	1993	3 yr.

* missing years	# POT series only from Flood Studies report

Data for the lower Lune exists from three separate sources; the Halton Upper Weir, Halton and Caton. The Halton Upper Weir recorded uncalibrated stage heights from 1940 to 1962. Microfiche records of the original chart records from Halton Upper Weir for the period 1951-1981 are held by the EA at Preston, these were examined and daily maximum stage heights were noted. A rating curve was not available from the Environment Agency and so the curve devised by Thompson (1984) was used. This rating curve was established by correlation with the gauges at Halton (1.1 km downstream) and Caton (2.5 km upstream) and based on revisions of the original rating equations developed by Peter Walsh of the then Lancashire River Board. The resultant discharges agree well with Thompson's records up to about 500 m^3s^{-1}, higher discharge estimates are not credible. However the higher discharges listed by Thompson do agree with those estimated by Chapman and Buchanan (1965) and so the flood record analysed in this study is that listed in Thompson (1984) for the period 1940-1959. It can only be assumed that some adjustment was required for the chart level data held by the E.A. the details of, which have been lost. However the uncalibrated daily maximum stage levels now exist in digital form.

From 1959 to 1979 flood data comes from computer printouts of daily mean, low and high flow from the new Halton gauge, archived by Thompson, the following detail of the gauge is taken from Thompson (1984). In 1959, the new gauging station at Halton came into operation, providing more reliable data, calibrated directly at the site by current metering from a cableway. In 1964, an old weir upstream collapsed, and the resulting debris washed downstream to affect the rating at this new site. To allow for this, the rating equations were changed from May 1966. The Halton gauge was well calibrated for high flows, both before and after the change, with only a few annual floods being outside the range of gaugings. Low flow readings were less accurate, however, and from 1968 a new compound broad crested weir at Caton (SD529654) was used to provide the record of flows below 17.25 m^3s^{-1}. The very small percentage difference in catchment area between the Halton and Caton sites, (995 km^2 and 983 km^2 respectively), justifies the use of such a combined record. From 1977 onwards, the Caton gauge was fully calibrated, and has now completely replaced the Halton station. Computer printouts of daily flows for Caton from 1976 to 1980 were also archived by Thompson; data for this study is taken from this source until 1979 until 1979. From 1979 to 1997 data comes from the computerised records kept by the Environment Agency.

The three gauges on the Lune therefore provide a more or less continuous record of discharge from 1940 to 1997. In addition there exists a valuable record of historical floods at Caton Low Mill (SD 527647), in the form of an engraved stone, set into the wall recording all occasions of flooding at the mill from 1892 to 1954. Unfortunately this stone has since been relocated. Chapman and Buchanan (1965) give estimates of discharge for these flood stages, and for a further four occasions of flooding between 1962 and 1965. Comparisons of the estimates for events occurring since 1940 with the records from Halton and Halton Upper Weir show the estimates to be, on average 7.5% higher than the recorded values (Thompson, 1984). The record at Caton Low Mill is therefore seen to be of reasonable accuracy, and extends the record of floods greater than about 780 m^3s^{-1} to 90 years.

For the sake of posterity, all the data associated with the gauges at Halton and Caton together with rating curves and notes from Alan Thompson and a summary of the record will be archived at Lancaster University Library, a copy will also be housed with the EA. All other discharge data is available digitally from the EA.

4.4.2 FLOOD FREQUENCIES AND EVENT POPULATIONS

Flood frequency has been analysed using a partial duration series rather than annual maxima (Shaw, 1994), all data were checked to ensure flood peak independence. The use of peaks over threshold (POT) series when examining flood frequency is recognised as an appropriate technique for examining changing flood frequencies over time (e.g. Gregory & Madew, 1982). It is usual to select all flood peaks and then to determine a threshold that produces floods that occur on average once a year, this is known as the annual exceedance series. There is some physical justification for this, return periods and duration of formative flows have been found to be within the range 1 to 2 years described by Wolman and Miller (1960). Hey (1975) observed that the return period for bank full floods in gravel bed rivers was around 1 year. However bank full floods for sand bed rivers can vary between 1 and 32 years. The bank full flow for the river Lune was exceeded nearly 200 times during the period 1940 to 1998. Werrity (1997) suggests that over medium to long timespans it may be flows of moderate magnitude and frequency that are responsible for driving morphological adjustments through sediment transport in large rivers. In terms of bank erosion, generally it has been found that the range of effective flows was bounded by stages corresponding to 'barfull' and bankfull flows at the lower and upper limits respectively. This means that an increase in 'medium' sized floods may have significance for fluvial geomorphic stability over decadal timescales.

The flood chronology for the Lune is listed in Table 4.4, data is from a number of listed sources and includes the dates of some notable floods recorded but not measured. The trend in flood frequency is shown in Figure 4.6 for the combined lower Lune record described in the previous section for the period 1892 to 1997 for all floods greater than 780 m^3s^{-1}. There is no statistically significant evidence that the size or frequency of large floods has increased during the last 100 years, although the period 1930 to 1970 saw a steady increase in the number of large flood events. If the threshold is taken as bankfull, (389 m^3s^{-1}), exceeded on average 3.5 times per year, a weak trend towards above average frequency can be seen from the late 1970s (see Figure 4.8). Previous work on the Lune (Thompson, 1984) has suggested that the only significant trends in flood frequency are those for intermediate sized events, this is supported by analysis conducted during this project.

Table 4.4. Flood Chronology for the Lune (events >780 m^3s^{-1})

Date	Magnitude (m^3s^{-1})	Description	Source
2.9.1892	966	Estimated peak discharge	Chapman & Buchanan
26.1.1903	1092	Estimated peak discharge	"
8.9.1903	784	Estimated peak discharge	"
10.2.1920	868	Estimated peak discharge	"
13.11.1923	1106	Estimated peak discharge	"
21.9.1927	896	Estimated peak discharge	"
3.11.1927	1036	1 mile wide at Arkholme	"

14.12.1936	980	Estimated peak discharge	"
9.10.1940	786		Halton, Thompson
22.11.1947	793		Halton, Thompson
18.10.1954	826	Estimated peak discharge	"
23.10.1954	826	Estimated peak discharge	"
2.12.1954	1148	Estimated peak discharge	"
11.8.1962	784	Estimated peak discharge	Chapman & Buchanan
9.12.1964	860		Halton PGS
12.12.1964	899		Halton PGS
17.12.1965	855		Halton PGS
24.3.1968	1022		Halton PGS
9.11.1972	801		Halton gauge
27.10.80	837	Halton flooded	Halton gauge
2.1.82	854		Caton gauge
19.2.90	875		Caton gauge
31.1.95	1182	Severe flooding	Caton gauge

Figure 4.9 shows the flood frequency trend for intermediate floods above 230 m^3s^{-1} and below 700 m^3s^{-1} for the period 1940-1997. The lower threshold was selected as being close to but below bankfull, determined by field observation and corresponds to a flow exceedence of about 1%, the threshold is exceeded on average 10 times per year. Two steps are apparent in the data one after 1950 and one after 1976, Thompson (1984) attributed these steps to intensified land drainage activity. The number of intermediate floods has remained above the average for the period, reaching a peak in the late 1980s. Notably the variability in the trend has been greater since the late 1970s.

Figure 4.7 Frequency of Lune Floods >780m $^3s^{-1}$

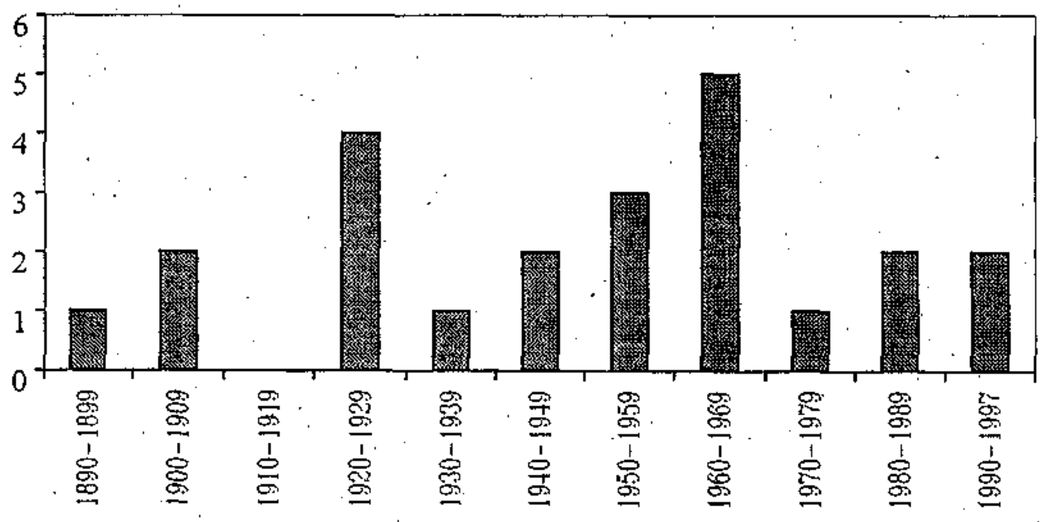
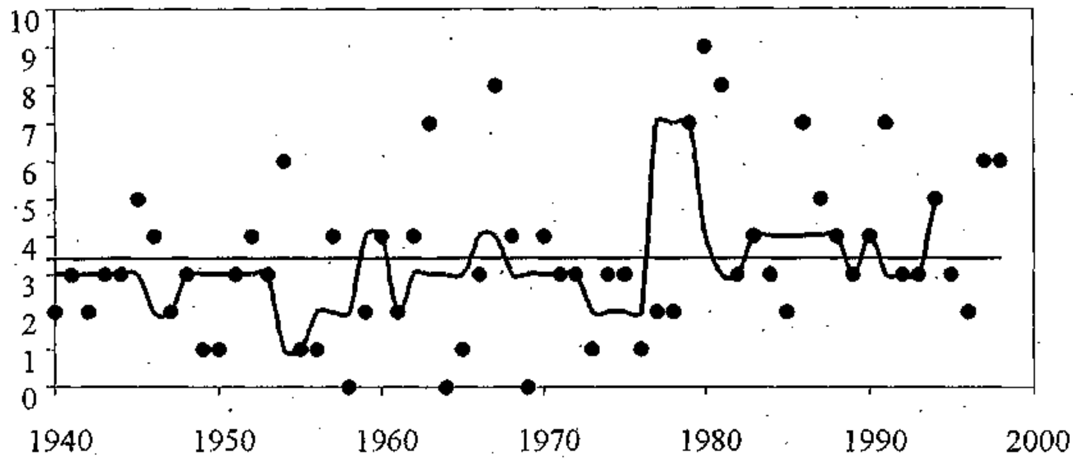


Figure 4.8 Number of floods over bankfull per year



If all flood events are examined together on a decadal scale an apparent trend exists shown in Figure 4.10, bearing in mind that the data for much of the winter of 1998 and the whole of 1999 are not included. The trend in flood frequency is also a reflection of the fact that the rivers discharge regime has become more 'event-based'. Indeed there has been an increasing number of days where low flows are experienced.

Figure 4.9 Intermediate flood frequency at Halton/Caton 1940-1998

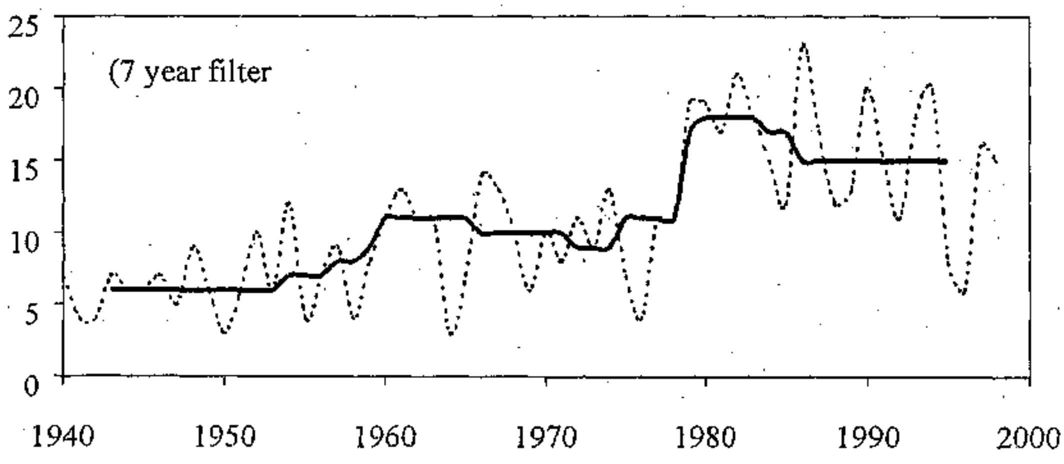
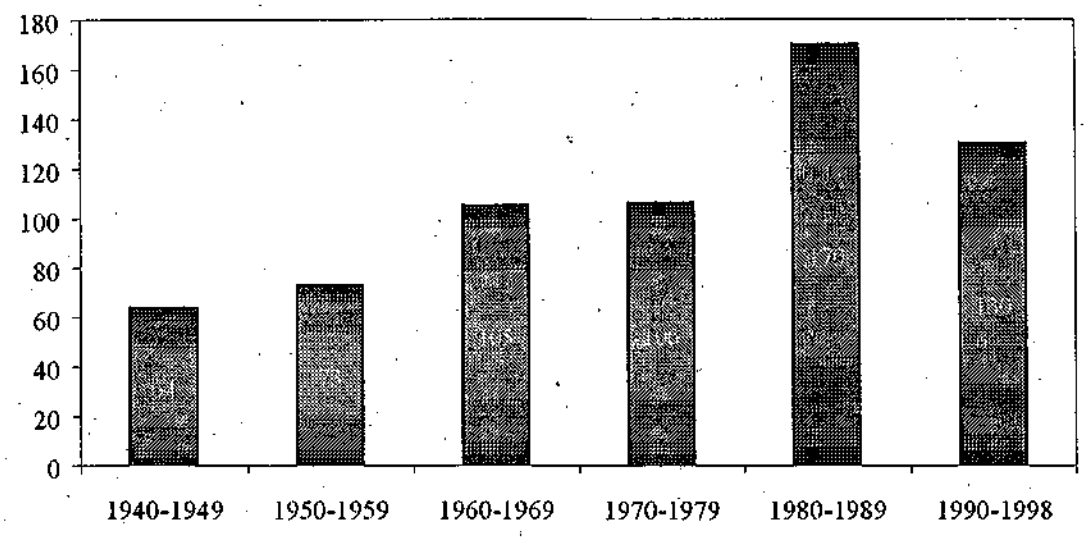
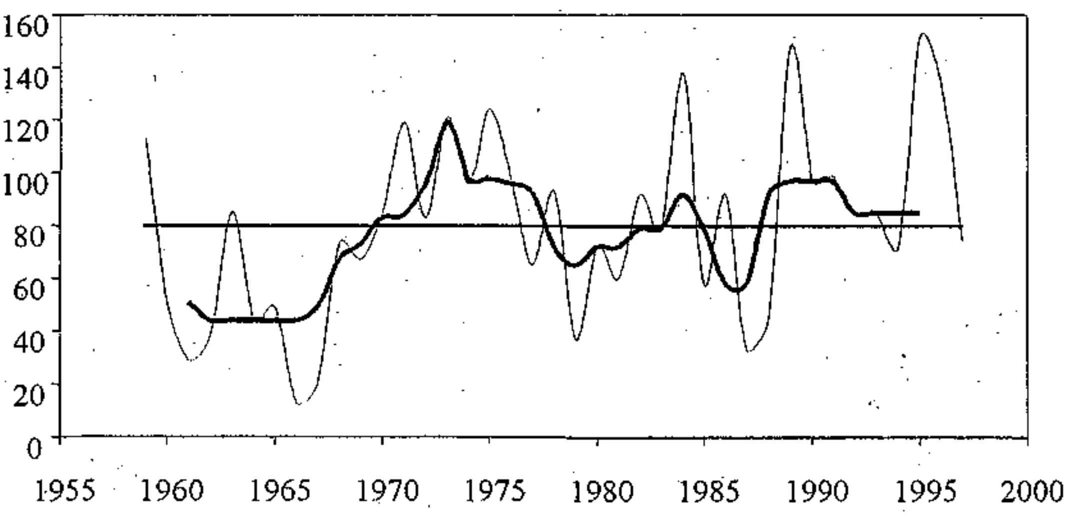


Figure 4.10 Frequency of all floods >230 cumecs at Caton from 1940-1998



Low flows may be expressed as the 95% flow i.e. the flow that is exceeded 95% of the time or as that exceeded 75% of the time (Shaw, 1988). Figure 4.11 shows the frequency of low flows at Q_{75} at Halton/Caton, which corresponds to a mean daily flow non-exceedence threshold of 7.5 m^3s^{-1}. Unfortunately low flow data are only available from 1959 for the Halton/Caton gauges. Three of the highest frequencies of high flows during 1984, 1989 and 1995 have been in years of very high flood frequencies emphasising the increasing variability in the discharge regime.

Figure 4.11 Q_{75} flows at Halton/Caton 1959-1997



Flood frequency analysis for the remaining gauging stations within the catchment was based on the number of floods occurring on average 2 to 3 times per year. An attempt was also made to determine thresholds for flood events close to bankfull, although this has proved to be problematic since there are very few ratings at this stage. Discharge records from the remainder of the catchment have limited value since they are of shorter duration and in many cases have missing data. Despite the limitations there are some clear trends in flood frequency between the upper and lower catchment. Figure 4.12 shows a selection of data from gauges in the upper catchment where it can be seen that in the last 20 years flood frequencies have tended to increase. This trend is reversed on the Wenning in the lower catchment (threshold >142 m^3s^{-1} 1957-1969, at Hornby, threshold >125 m^3s^{-1}, 1976-1996 at Wennington).

Figure 4.12a POT series for upper Lune catchment

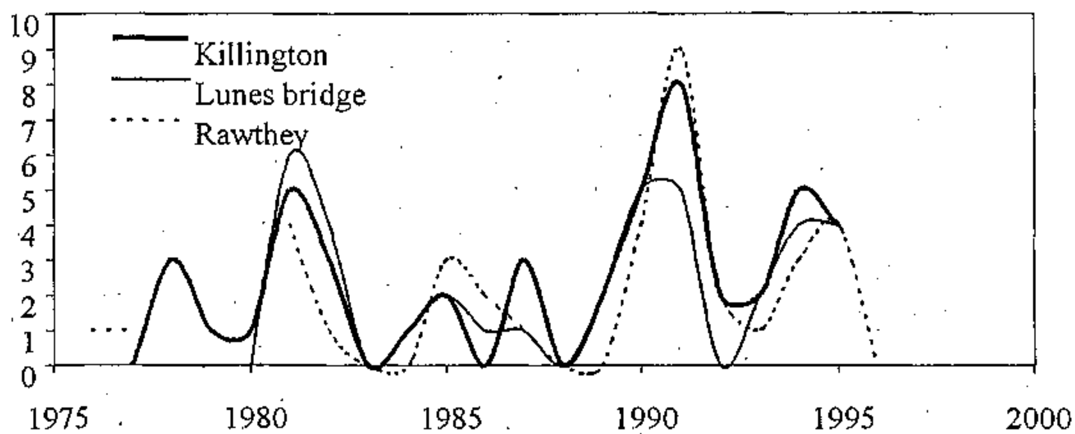
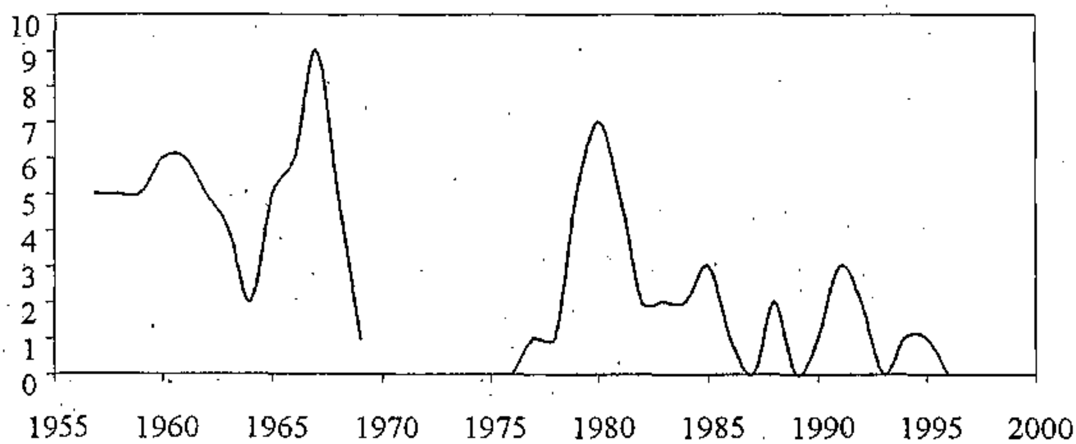


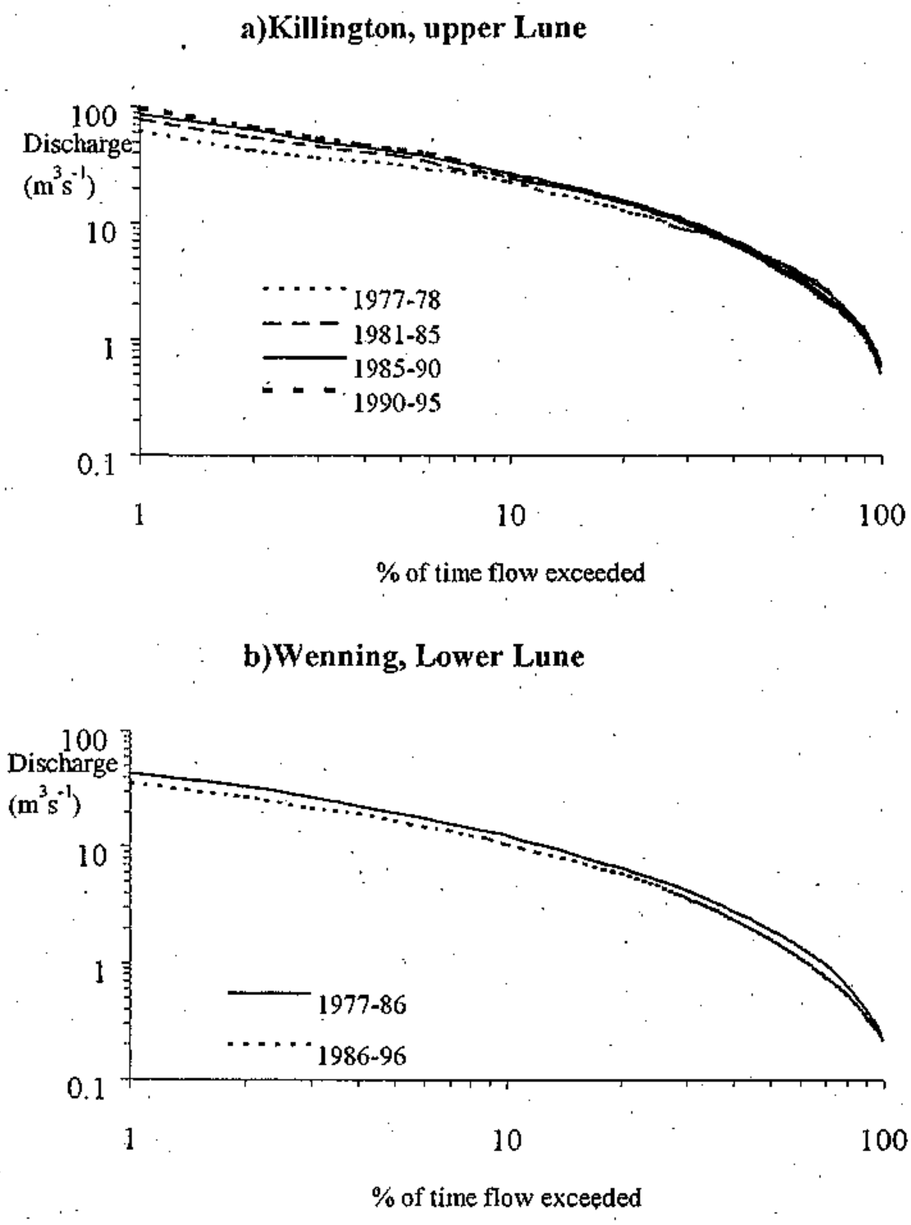
Figure 4.12b POT series for lower Lune catchment



4.4.3 DURATION SERIES AND SEASONALITY

Discharges that are sufficient to transport bedload material are also likely to be important for bank erosion. The duration of events above the threshold for bedload movement have been shown to relate to bank erosion rates more closely than the peak magnitudes of the events involved (Lewin, 1989). The duration of high flow events has traditionally involved hydrograph analysis, unfortunately digitised hydrograph data are only available for the period since 1976 and it is widely recognised that separation of baseflow and storm flow to produce unit hydrographs is highly problematic (Beven, 1991). Beven recommends the use of time series analysis in examination rainfall-runoff an approach adopted in this study and described in section 4.6. However the use of flow duration curves also has some value. Flow duration curves, from the upper and lower Lune catchment illustrate the changing nature of the flow duration curve which is most obvious for those flows exceeded less than 10- 20% of the time, shown in Figure 4.13. Killington, in the upper catchment, exhibits a progressive increase in the size of floods that are exceeded less than 10% of the time, the river Wenning shows an opposite trend.

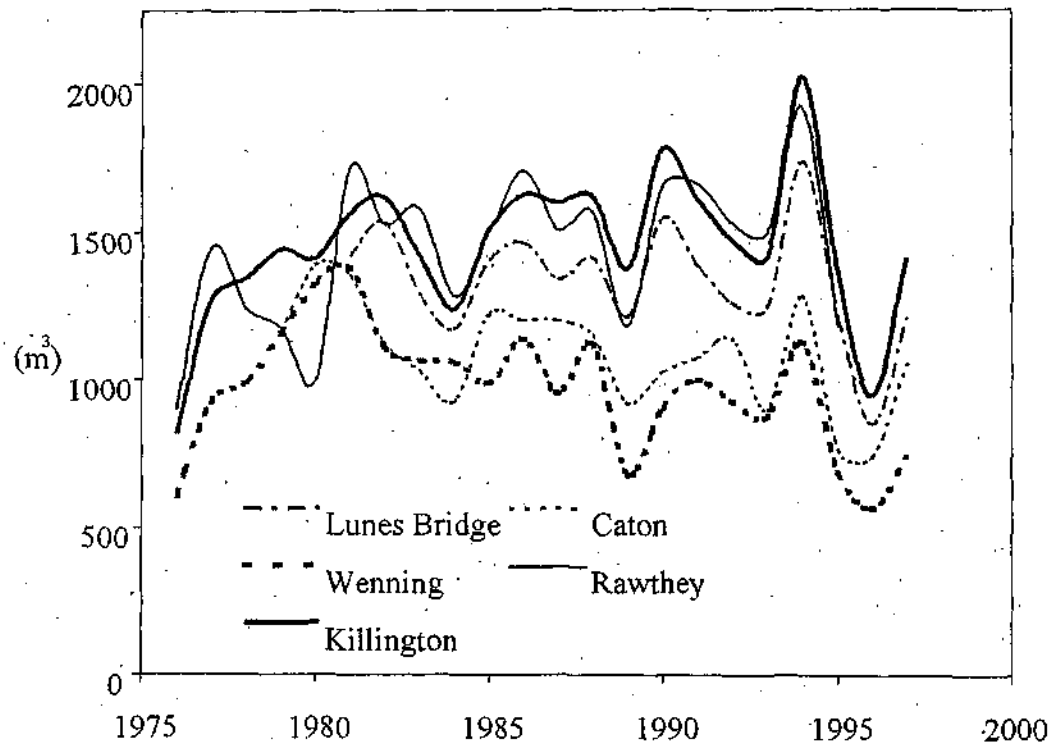
Figure 4.13 Flow Duration curves



4.4.4 CHANGES IN RUNOFF

Trends in total annual runoff for the different areas of the Lune catchment are shown in Figure 4.14, it can be clearly seen that total discharge has been declining in the lower catchment (Caton and Wenning) whereas all stations in the upper catchment are increasing. Effectively the increased runoff in the upper catchment is not sustaining the levels of total discharge at the catchment outlet; the middle catchment

Figure 4.14 Total annual runoff

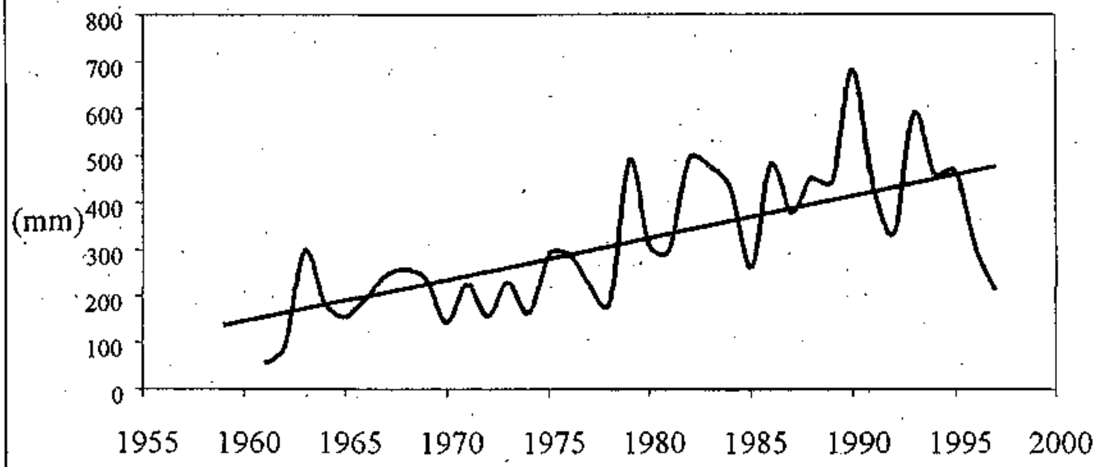


is acting as a sink. This may be related to water abstractions in the middle and lower catchment, although these are not thought to be extensive. The major abstraction from the Lune is downstream of the Caton gauge. It may be that rainfall in the lower catchment has been declining over the period of record for discharge shown here (i.e. since the late 1970s, shown on the Austwick gauge in Section 2). However rainfall at Morecambe has been increasing during this period, examination of the relationship between rainfall and runoff helps to explore this issue.

Monthly mean discharges from a catchment area can be converted to volumes of water produced and then to equivalent depths over the catchment area. Rainfall and runoff in the same units can then be compared (Shaw, 1994). Rainfall falling on a catchment is usually expressed as a depth (P, mm), but may be converted to a volume of water, m^3 falling on the catchment. Alternatively discharge, in m^3 s^{-1} may be converted, for a comparable time period, into total volume m^3 and expressed as an equivalent depth of water over the catchment area in mm (Q). When examining rainfall and runoff on a monthly basis the loss of water to evaporation and storage is equal to the rainfall minus the runoff. However the months March to September generally show the loss to be due to evaporation, during the winter months the loss is due to groundwater recharge. When winter months are combined in the UK significant relationships between rainfall and runoff can be obtained (Shaw, 1994), regression functions and the resulting correlation coefficients can be determined. When annual data are examined the seasonal effects and groundwater considerations may be neglected. Hudson and Gilman (1993) used P-Q to explore the long-term variability in the water balances of the Plynlimon catchments in Wales; the same approach is adopted here. This assumes that the resultant trend is that of actual evapotranspiration

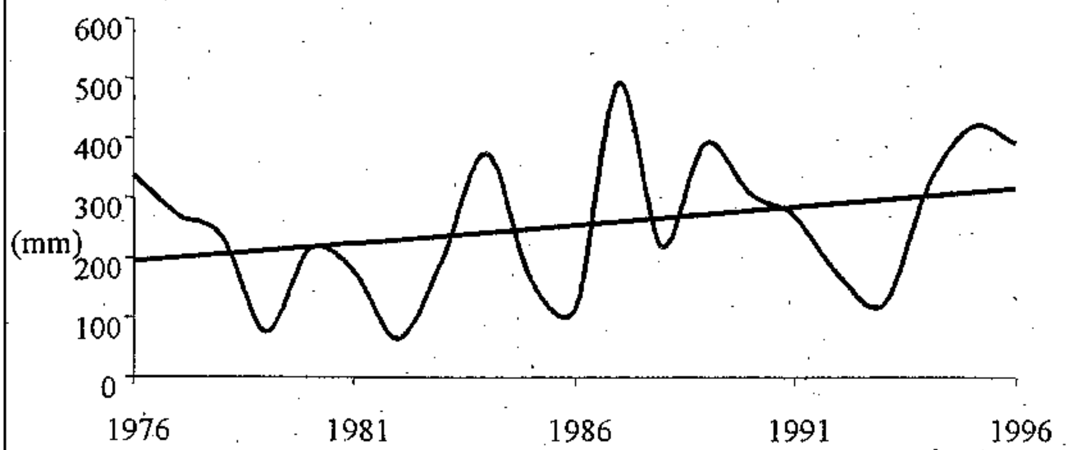
The rainfall runoff relationship for Caton from 1959 to 1997 is shown in Figure 4.15, clearly, runoff is declining relative to rainfall.

Figure 4.15 P-Q at Halton/Caton, lower catchment



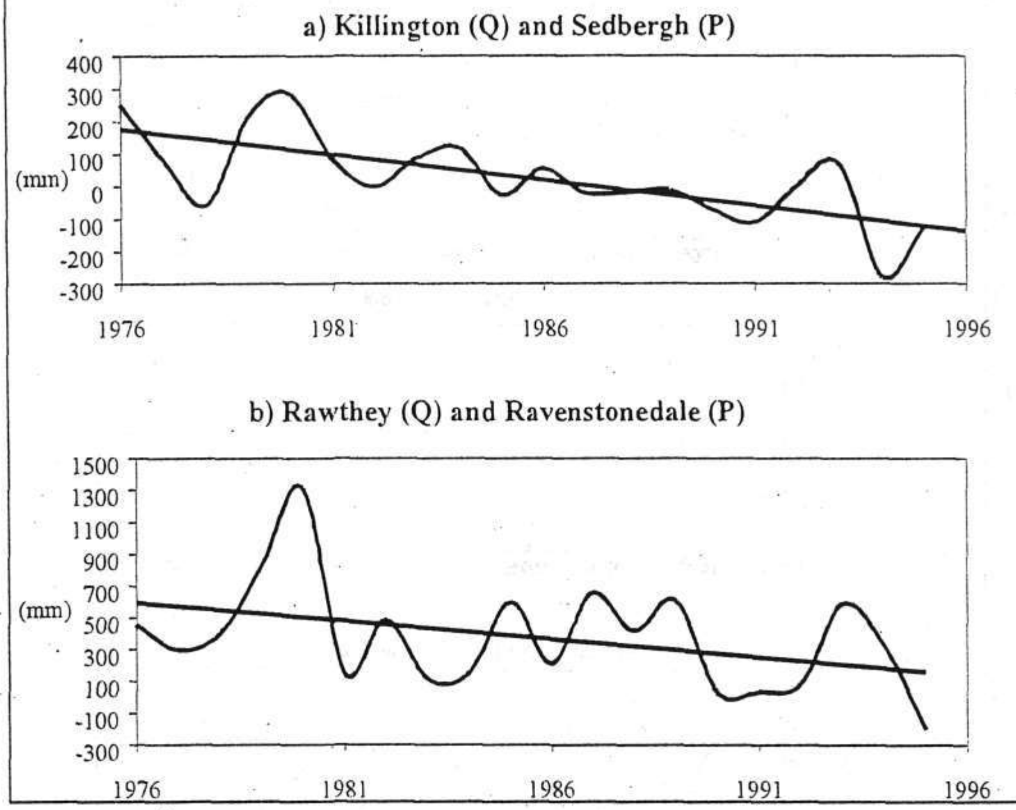
The example in Figure 4.15 uses rainfall data from Sedbergh in the upper catchment; the trend is the same however using rainfall from Morecambe. The same trend is obvious from Wennington in the middle Lune catchment, shown in Figure 4.16. In both cases actual evaporation has been increasing which may be a result of increased average annual temperatures over recent decades, it has been observed elsewhere that elevated temperature can lead to reduced average runoff (LeRoy Poff *et al*, 1996).

Figure 4.16 P-Q at Wennington, middle catchment



Hudson and Gilman (1993) found an opposite trend in actual evaporation for Plynlimon with decreases over the period 1969 to 1988. Data from the upper Lune catchment mirror the trend from Plynlimon. The results of analysis are presented for only two discharge gauging stations using two different rainfall records in the upper catchment (Figure 4.17a and 4.17b). These trends are believed to be robust as they are based on combining rainfall and flow records from stations most closely aligned with each other in catchment location. However the same analysis was conducted with different combinations of all records in the upper catchment; the trend in actual evaporation is consistently downwards.

Figure 4.17 P-Q, upper Lune catchment



4.4.5 TIME SERIES ANALYSIS

The data presented in previous sections on rainfall and runoff exhibit considerable variability around a mean value. There appears to be a non-stationarity associated with the mean for runoff data and there may also be non-linearity in the data about this non-stationary mean, i.e. a trend in the seasonal component of rainfall and runoff. Simple plots of long term time series can give an impression of overall gross trends in the data, however some trends will be more subtle. Consequently the aim of this section is to identify and quantify the extent of less obvious trends within rainfall and runoff and then to examine the correlation between the two series. After consideration of the inherent non-linearity always present between rainfall and runoff within a catchment as a result of antecedent conditions, differences in the two trends may, in principle, be attributable to land use changes.

Many conventional methods of time series analysis have been devised for stationary data. A stationary time series is one in a state of statistical equilibrium, strictly speaking this must mean that its statistical properties are unaffected by any change in the time origin (Young, 1993a). A non-stationary time series may change in some manner over any selected observation interval.

The long-term trends in rainfall and runoff are obviously similar and are shown in Figure 4.20 for Sedbergh (rainfall) and Caton (runoff).

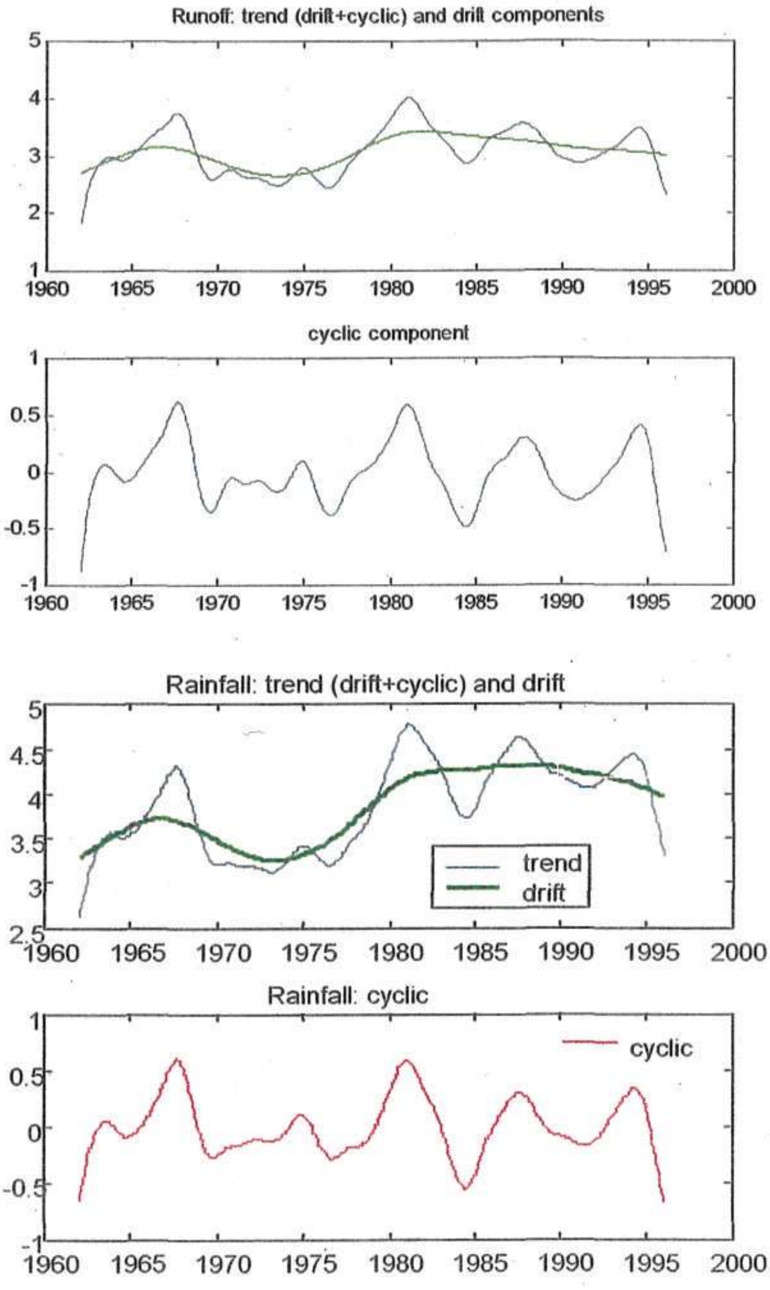
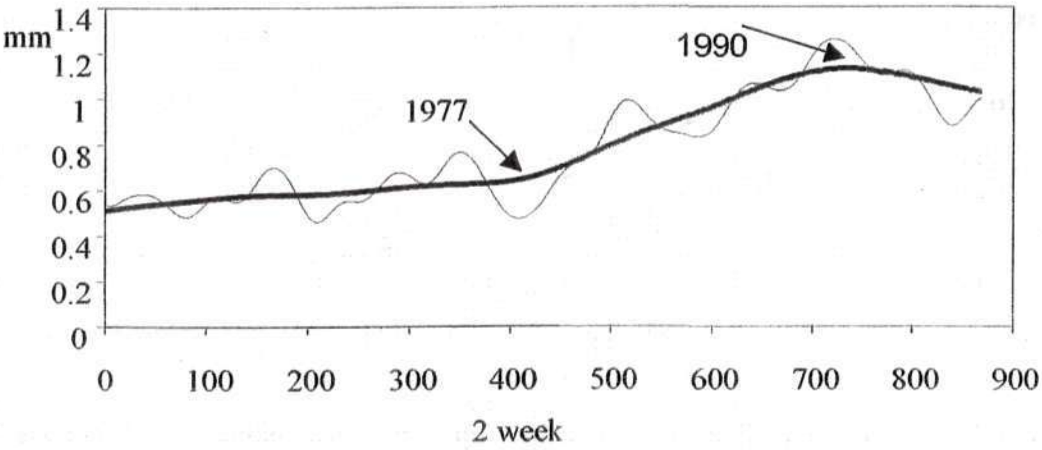


Figure 4.20 Rainfall and runoff trends

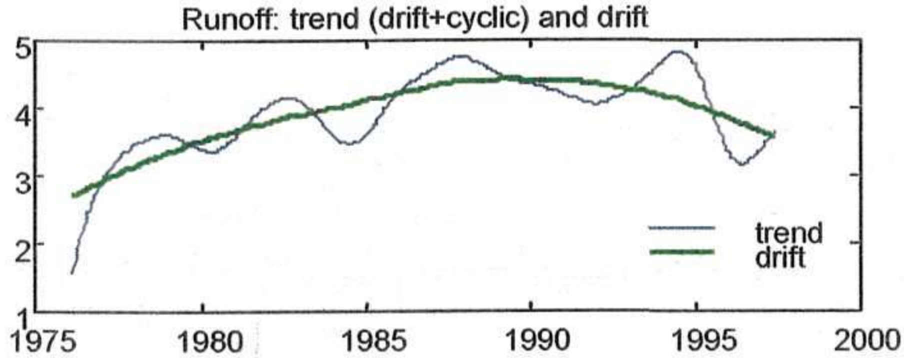
The trend in total daily runoff (scaled with catchment area) for Caton from 1962 to 1995 is shown in Figure 4.21. A distinct trend can be seen in the runoff response, which was shown previously as the P-Q relationship.

Figure 4.21 long term trend in runoff response 1962-1995



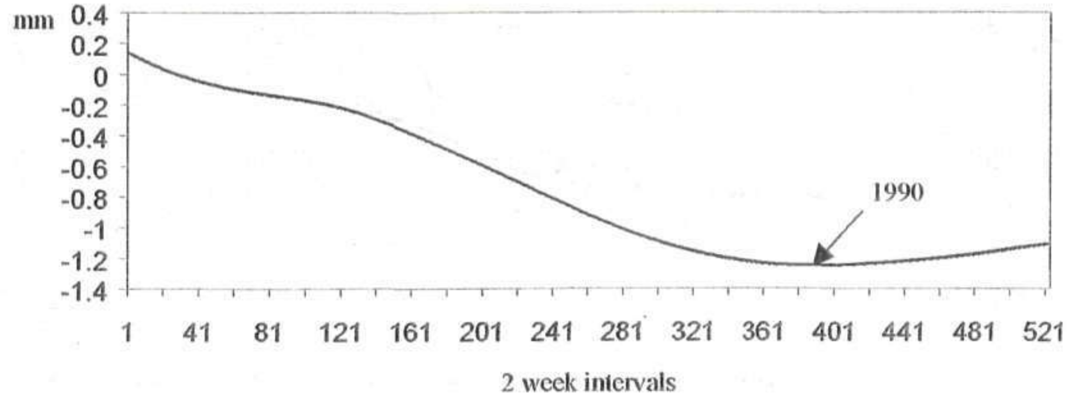
The data is total annual runoff scaled to catchment area, the time series analysis methods used, decimate the data to 2-week intervals; the bold line is the long-term trend and the feint line is the variability in the residuals calculated from the dynamic harmonic regression model. Between 1962 and 1977 runoff was decreasing relative to rainfall (upwards trend in Figure 4.21), this trend became more pronounced between 1977 and 1990 after which it was reversed. In conclusion, since 1990, there has been an increased amount of runoff at the catchment outlet, which cannot be directly related to the total annual rainfall. The runoff trend for Killington in the upper catchment is shown in Figure 4.22, increasing between 1976 and 1990 and then declining.

Figure 4.22 Runoff at Killington



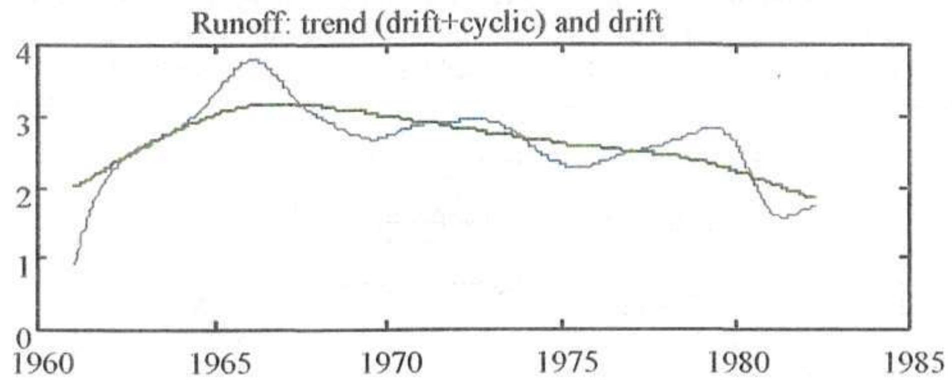
It was shown earlier that the runoff response in the upper catchment was showing an increased amount of runoff from 1976, the results of comparison from the rainfall (at Sedbergh) and runoff models for Killington (P-Q) are shown in Figure 4.23. It can clearly be seen that total annual runoff has been increasing relative to rainfall until 1990 when the trend appears to be changing.

Figure 4.23 Runoff response at Killington 1976-1995



The trends in rainfall distribution within the Lune catchment have been discussed in Section 2 where it was noted that the middle and eastern side of the catchment were subject to a different rainfall trend. The runoff trend for the River Wenning is shown in Figure 4.24 and the strength of seasonal components in the runoff is shown in Figure 4.25 with confidence limits.

Figure 4.24 Runoff, River Wenning



The strong seasonality observed in the upper Lune catchment, particularly between the late 1970s and the 1990s, is not present in the discharge of the River Wenning, which has been declining since 1965.

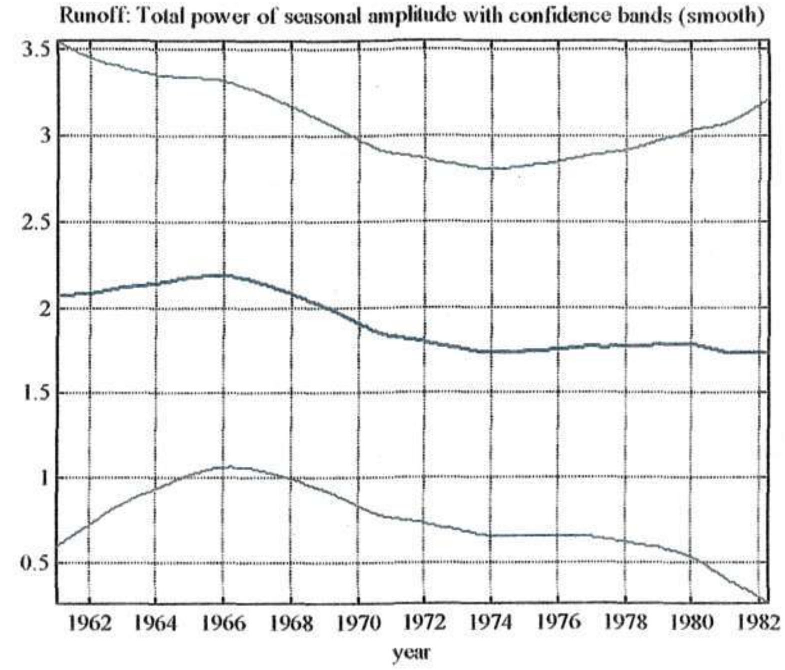


Figure 4.25 River Wenning, seasonal components of runoff

4.5 FLOOD GENERATING MECHANISMS

In order to examine the flood generating mechanisms the pre-flood weather types have been listed in Table 4.5, these relate to the series of large floods only.

Table 4.5 Pre-flood weather types for largest known floods 1892-1994

	Prevailing weather type on days leading up to a flood			
Flood Date	**3**	**2**	**1**	**Day of flood**
2.9.1892	C	C	W	W
26.1.1903	W	W	W	W
8.9.1903	W	AW	W	W
10.2.1920	S	W	W	W
13.11.1923	W	SW	W	CW
21.9.1927	W	W	W	C
3.11.1927	W	SW	SW	W
14.12.1936	W	W	W	W
9.10.1940	C	W	W	C
22.11.1947	U	SW	SW	W
18.10.1954	C	C	S	CW
23.10.1954	W	W	W	CW
2.12.1954	S	C	W	W
15.2.1958	W	S	C	CW
11.8.1962	W	CW	CW	CW
9.12.1964	W	W	W	W
12.12.1964	W	CW	W	W
17.12.1965	ASW	S	W	W

24.3.1968	C	W	W	SW
9.11.1972	W	W	AW	W
27.10.1980	C	A	S	SW
2.1.1982	SE	SE	C	S
19.2.1990	SW	SW	SW	SW
31.1.1995	C	C	A	SW

For the period up to and including 1972, the predominant pre-flood weather types were westerly and cyclonic westerly, the most frequently occurring weather type on the preceding and the day of the flood is the westerly type (Tables 4.6 and 4.7). However since the early 1970s the flood generating weather types appear to be south westerly (Table 4.8.).

Table 4.6 Weather types preceding floods between 1892 and 1994

	W	C	CW	SW	S	AW	A
Flood day	12	2	5	4	1	0	0
Previous day	14	2	1	3	2	1	1

Table 4.7 Weather types preceding floods between 1892 and 1973

	W	C	CW	SW	S	AW	A
Flood day	12	2	5	1	0	0	0
Previous day	14	1	1	2	1	1	0

Table 4.8 Weather types preceding floods between 1972 and 1998

	W	C	CW	SW	S	AW	A
Flood day	0	0	0	3	1	0	0
Previous day	0	1	0	1	1	0	1

The close correlation between southwesterly weather types and flood frequency does not wholly explain the trend in flood frequencies. The upward trend in intermediate floods is apparent from 1940 onwards. The increase in southwesterly weather (combined with an increase in cyclonicity) may explain the rapid rise in flood frequencies from 1970 onwards. However, the general upward trend in flood frequency cannot be accounted for by climatic change and so is attributable to landuse activities. Prevailing weather types associated with intermediate floods are shown in Tables 4.9 and 4.10, where figures are expressed as the percentage of intermediate floods preceded by the named weather type.

Table 4.9 Intermediate floods between 1940 and 1969

	W	C	A	S	N	E
Flood day	39.06	45.92	3.43	7.3	2.15	0
Previous day	45.92	27.04	10.73	8.15	4.29	0

Table 4.10 Intermediate floods between 1970 and 1998

	W	C	A	S	N	E
Flood day	38.59	39.67	2.45	14.67	3.26	0.27
Previous day	44.29	22.55	8.42	12.77	4.08	0.27

4.6 DISCUSSION

There is clear evidence form the Lune catchment that the flow regime has changed over the last 50 years. An increase in the frequency of intermediate flood events is matched by an increase in the number of low flow days so that the regime has effectively become more "flashy" or event based. This increase in flood frequency is not related to trends in rainfall except for the period after 1976.

The first notable change in the flood frequency occurs around 1950 which is also the time following the greatest land drainage activity. The complexity of runoff response to land drainage activity has been discussed in section 3 and it was noted that the response is highly variable. There is considerable debate about the precise impact of field and moor drainage on flood peaks and how far down a catchment these effects are noticed. The only conclusive studies are taken from small catchment studies where local conditions (soil, geology, etc.) are of primary importance in determining the effects on the flood hydrograph. It was however noted by Bailey and Bree (1981) that the major increase in flood peaks was channel improvement itself. It is known that extensive channelisation work has been carried out on the Lune particularly in the tributary headwaters (e.g. Wenning and upper Lune). It is not possible to precisely quantify the effects of land drainage or to separate them from the effects of increased intensification of farming however it is clear that human factors and not climate change are responsible for changes in the flow regime after 1950 and up to 1976. These changes are measurable at the outlet of this large catchment.

The last 25 years have been the most climatically variable this century and after 1976 the trends in flood frequency appear to reflect this climatic variability. However the actual amounts of rainfall do not necessarily explain the trend it is the frequency of more intense rainfall that is reflected in the flood frequency. It is possible that if the current high frequency of intense rain declines over the next few decades then the flood frequency will drop back to the level observed in the 1960s. According to climatic predictions this is the unlikely scenario. The effects of land use may still be producing a strong signal in the upward trend in flood frequencies as it is not known how long the impacts will continue to cause changes. Whatever the future climatic conditions unless channelisation is removed and drains infilled, the regime will remain one of short duration flood events and long periods of low flow. The current trend of reduced summer rainfall and increasing winter rainfall exaggerates the effects already felt as a result of land use changes.

In addition the runoff response has become spatially variable within the catchment with overall reduced runoff at the catchment outlet and increased amounts of runoff in the upper catchment. The potential for increased upland runoff to contribute higher levels of suspended sediments has been discussed previously, reduced runoff in the lower catchment may add to any potential siltation problems. In the past it has generally been accepted that flood events "clean" river gravels, if degraded upland areas are contributing high levels of fine sediment, flood flows may lead to infiltration of fine material to the bed. The amount of fine sediment from upland runoff contributing to gravel siltation is not well reported and requires further investigation.

Discussions of future climate change highlight the probability of current extremes of weather becoming more frequent. This could mean that localised intense storms leading to flooding could become more frequent at the scale of e.g. the 1967 Wray floods, the 1982 Howgill floods, the 1995 Hornby flood, and the 1998 Lancaster and Galgate floods. Duckworth and Seed (1969) reporting on the causes of the Wray flood refer to the degraded state of the fells as being a major contributory factor in the rapid runoff experienced in this flood. The impacts of channelisation, land drainage and reduced upland vegetation may become still more significant under climatic scenarios with greater extremes as a greater percentage of rainfall contributes to the quickflow component of flood hydrograph. Such extremes are predicted to occur within the next 20 to 50 years.

4.8 SUMMARY

Flood frequencies have increased in the Lune catchment over the last 50 years notable "steps" have occurred in 1950 and 1976. The former is most likely a result of land drainage and channelisation, changes after 1976 appear to reflect trends in increased amounts and intensities of winter rainfall. The contribution of land use activities to the increased flood frequencies between 1976 and the early 1990s is difficult to separate from the climatic variability.

Increased flooding and a greater number of low flow days particularly in summer have produced a more "flashy" regime. The flood regime is likely to have increased the amount of time when stream power is sufficient to cause erosion increasing the risk of bank erosion and fine sediment production.

Runoff within the Lune catchment is spatially variable with reduced runoff in the lower catchment and increased runoff in the upper catchment. There may be greater evaporation and abstraction in the lower catchment whereas runoff in the upper catchment may be responding to greater rainfall intensities and possibly to reduced vegetation cover. There appears to be some change in these trends around 1990.

Seasonal extremes in runoff are most significant in the upper areas of the Lune catchment, those that are most subject to orographic enhancement of rainfall. Seasonal extremes are not significant in the lower catchment e.g. on the River Wenning.

SECTION 5 FLUVIAL GEOMORPHOLOGY AND EROSION

5.0 INTRODUCTION AND OBJECTIVES

Extrinsic influences on catchment hydrology and changing discharge regime have been discussed in previous sections. The physical manifestation of extrinsic change is most visible in changing fluvial geomorphology and sediment regime. This section reviews processes in fluvial geomorphology and causes of instability. The extent of change within the Lune catchment is investigated with particularly emphasis on the spatial distribution of erosion. Geographic Information Systems (GIS) are used to assess the role of engineering work in causing or exacerbating channel stability problems.

The sedimentology and morphological characteristics of a catchment are dependent on the geologic and geomorphic history, sediment supply, through runoff and land use, and location within the catchment. Schumm (1985) summarised the river catchment as a series of zones based on dominant processes shown in Figure 5.1.

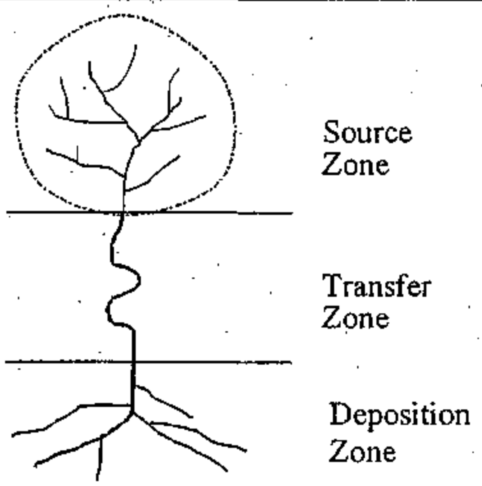


Figure 5.1 River catchment zones (Schumm, 1985)

River channels may also be defined, to some degree, by their location within the catchment; principal controlling factors are valley slope, valley shape and the width of the floodplain. The major processes operating in Schumm's catchment zones have been expanded by Sear and Newson (1993) and are shown in Figure 5.2. Following sections will discuss in some detail the processes defining channel planform, channel morphology and bank erosion and finally geomorphic thresholds and adjustment to system disturbances.

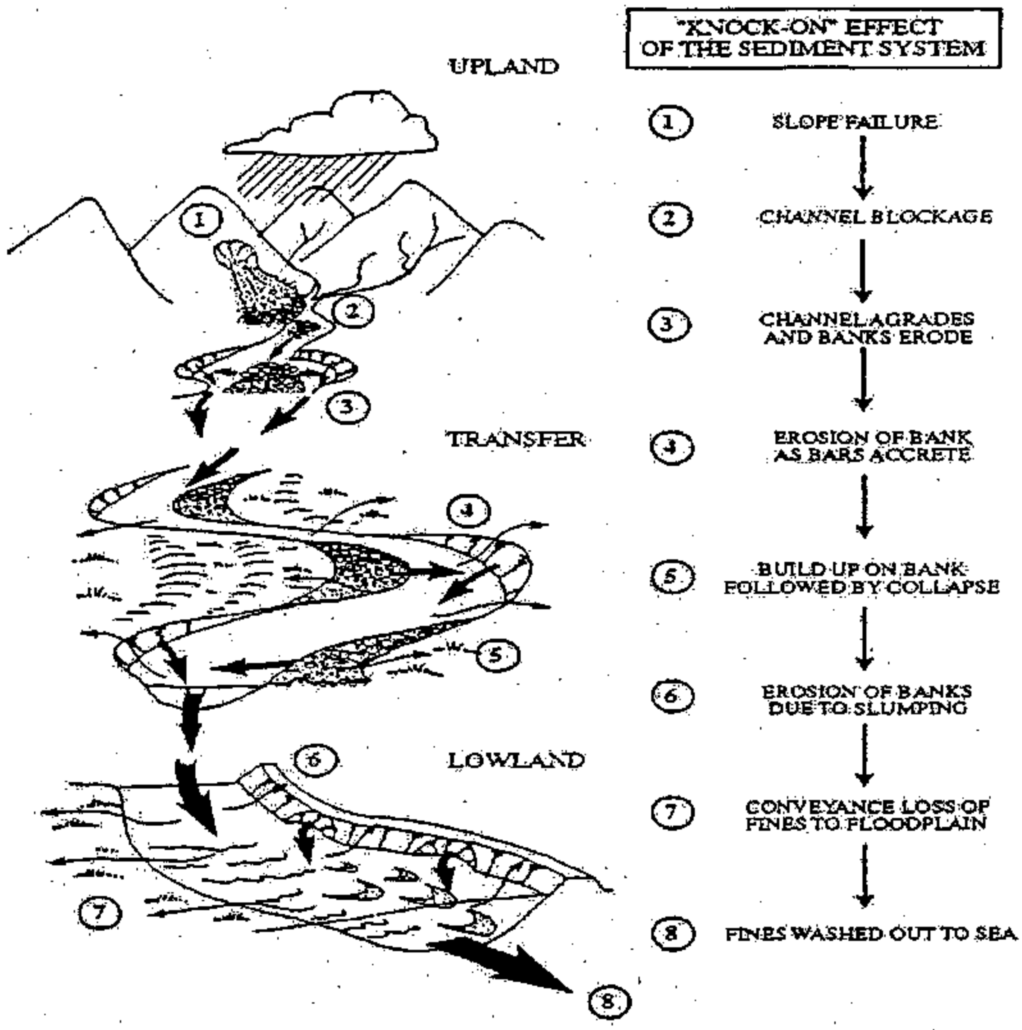


Figure 5.2 Typical process – response effects within the sediment system (after Sear and Newson, 1993)

5.1 CHANNEL PLANFORM

Thorne and Lewin (1979) described channel change as a sediment transfer process involving bank failure, sediment entrainment, transport and deposition. Extensive research has been conducted into river channel patterns and channel planform. Although many of the laws of meandering are known, geomorphological theory is unable to predict planimetric changes in river channel patterns (e.g. Hicken, 1977). Although important studies in planform geometry began earlier this century (e.g. Inglis, 1949); the classification of channel pattern and planform has been heavily influenced by the definitions of Leopold and Wolman (1957). Leopold and Wolman recognised three major types, meandering, braided and straight where sinuosities greater than 1.5 led to meandering forms. The limitation of this classification was noted by the authors (Leopold et al, 1964); they recognised that of 50 meandering rivers examined, half had sinuosities below 1.5. In practice river channels may have reaches that exhibit the whole range of sinuosities that determine whether it is meandering, braided or straight. The original definition of straight channels acknowledged that they rarely exist in nature for a distance of more than a few channel widths. The purpose of these classifications was a first step towards identifying the sedimentary and hydraulic processes that determine channel morphology and planform shape.

It is known that all aspects of channel geometry are related to the sediment and discharge regime however the link with channel planform is less clear. Many theories have been developed to describe different forms of meander development. Theories of free meander geometry derived from theoretical physics of flow, are useful but have limited applicability, as non-uniformity in meander bend form is common. The process of meander growth has been described (e.g. Hooke, 1995) based on field evidence. However there are still many unanswered questions relating to the initiation of meanders. It is known that channel patterns are the integrated outcome of hydrological regime, sediment load and channel boundary material composition. Hydrological and sedimentary regimes are controlled by physico-geographical factors of river basins, the channel boundary conditions are determined by previous activity of the channel. River basin factors include climate, geology, topography, vegetation, soils and human activity. The fact that amongst these factors, climate, vegetation and soils are related to geographical position has been used to investigate the probability of channel patterns occurring because of their location (Xu, 1995). The majority of research in channel pattern development has followed a deterministic approach concentrating on mechanical analysis. The result has been the documentation of a large number of site specific instances of change. The great complexity of process interactions has left gaps in knowledge about the general nature of different styles of adjustment or their relative sensitivity to drainage basin controls (Downs, 1995). This gap is highlighted in a recent review of mathematical models of meander development (Mosselman, 1995). Models are largely site specific and do not take account of the decrease in stream power associated with the maximum amplitude of meander development which occurs when the power to erode banks is reduced as a result of reduced channel gradients (e.g. Ikeda *et al*, 1981; Crosato, 1990).

Some researchers have adopted a probabilistic approach towards elucidating processes of planform development. Begin (1981) used the relationship between discharge (Q) and slope (S) (equation 5.1) to predict the probability of channels being of a particular pattern. The relationship is derived from a measure of shear stress and uses sinuosity to describe channel pattern.

$$S = 0.00506Q^{-0.327} \qquad \text{(Equation 5.1)}$$

A number of other equations have been developed to determine channel pattern based on slope and discharge specifically for gravel bed rivers (e.g. Bray, 1982; Ferguson, 1984). Thorne (1997) notes that such equations have been subject to considerable criticism in the literature but they do add a more quantitative dimension to the often-qualitative theories of planform development and change. Thorne adds, that those equations incorporating the importance of grain size are more useful (e.g. Ferguson 1984; Fredsøe, 1978). A review of many of these equations was undertaken by Smith (1987) who concluded that, Ferguson's equation for gravel bed rivers was most reliable and useful, as it does not require knowledge of width and depth (see equation 5.2 where D_{50} is the median bed material grain size).

$$S = 0.042. Q^{-0.49}.D_{50}^{0.09} \quad \text{(Equation 5.2)}$$

A further method for predicting channel planform has been proposed by van den Berg (1995) using median grain size and potential specific stream power based on bankfull discharge and valley slope (see equation 5.3). The equation defines the threshold between meandering planform with sinuosity > 1.5 and less sinuous braided rivers:

$$\omega_{vt} = 843\ D_{50}^{0.41} \quad \text{for gravel bed rivers} \quad \text{(Equation 5.3)}$$

where ω_{vt} is the specific stream power at the transition between meandering and braiding (W/m^2). This equation is only applicable to rivers where $Q > 10\ m^3.s^{-1}$ and 0.1 mm < D50 <100 mm. The combined use of stream power and sediment size accounts for some degree of the rivers competence to entrain and transport sediment (Thorne, 1997). Brookes (1995) reported that as a general rule channel slopes below 2 m per km will not have the power for channel change. However channel slopes are locally highly variable so that taking reach average values for slope may be misleading.

Graf (1984) also uses a probabilistic approach, based on historical maps to estimate parcels of land likely to be eroded. This "zoning" of the river has more recently become known as the "streamway" concept and linked to theories of continuity in river systems. Xu (1995) explored the relationship between channel pattern and latitudinal position in China and described morphogenetic zones where particular patterns were likely to dominate. Downs (1995) using a similar approach attempted to examine changes in the River Thames basin in heavily modified channels. In the Thames, channels regulated by low weirs were most likely to be dominated by deposition where gradients are lower than 0.0040, above this threshold channels are morphologically inactive. In channels straightened this century deposition is most likely in gradients below 0.0050, whereas erosional enlargement is most probable above this value. In channels initially channelised prior to this century, deposition gives way to stability at a threshold gradient of 0.0080.

The recognition of channel planform is important for river engineering and management activities; most of the recognised channel patterns have been classified by Brice (1975) and are shown in Figure 5.3. However, Thorne (1997) notes the importance of consideration of the longitudinal slope in any classification. Such a classification has been widely used in the United States, developed by Rosgen (1994). Rosgen has received some criticism for his classification system (Miller and Ritter, 1996) which may have been used for predictive purposes outside the reach of its applicability. Most of the equations listed and the classifications mentioned are useful in describing river channels and making some predictions for river restoration work, but they should be used as a guide and not definitive design criteria.

Studies of river instability as a result of anthropogenic interference have highlighted a number of processes that occur at certain thresholds; the most interesting being channel recovery. Where channels have been straightened or shortened, it is usually only a short time before the river attempts to dissipate its increased energy by developing alternate bars or regularly spaced riffles and ultimately, reasserting meanders. Often channelisation works are accompanied by hard, bank revetments; where these cannot be undercut, meander development or growth may be initiated downstream or headcut erosion upstream (see Section 3).

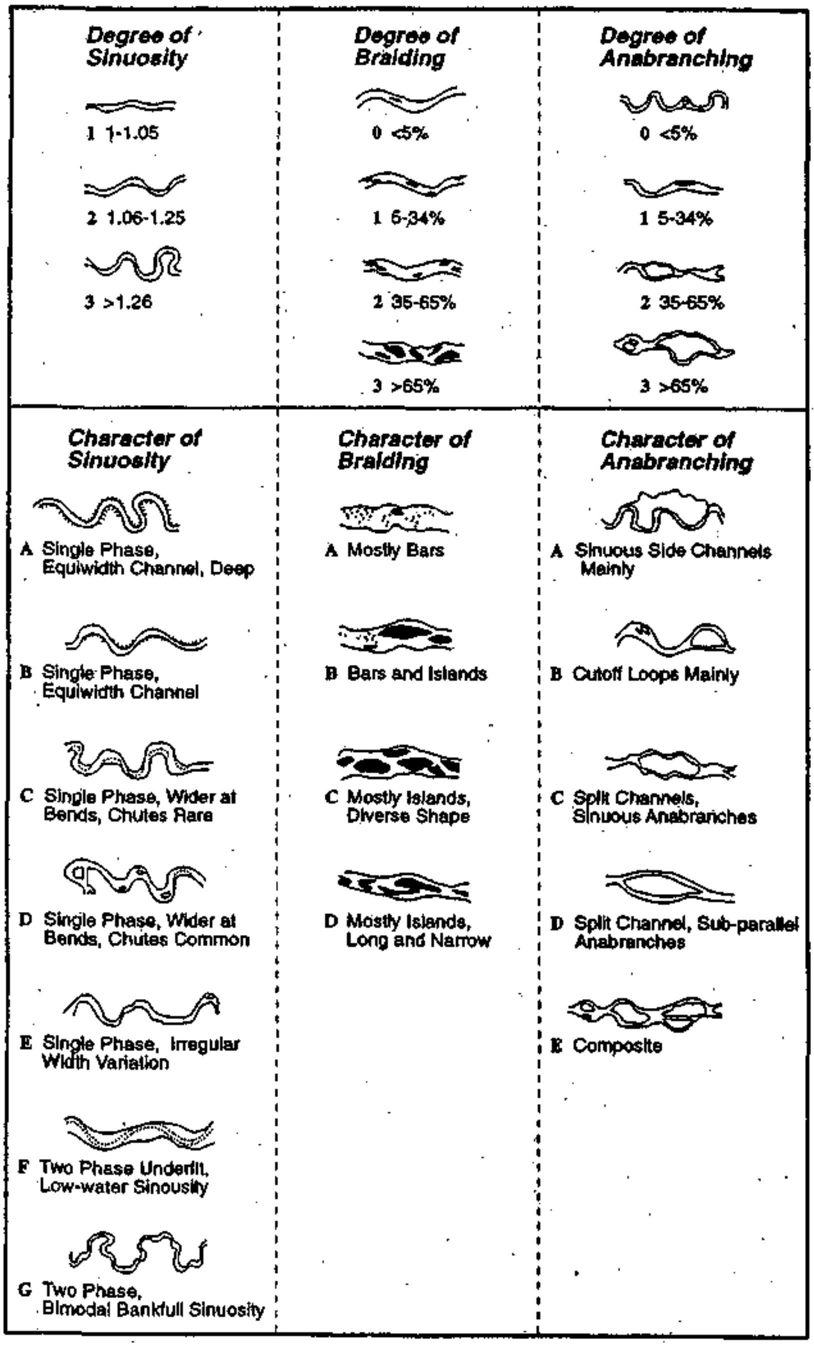


Figure 5.3 Channel pattern classification (after Brice, 1975)

Sweeping meander bends generally occur in the piedmont zone (Schumm's transfer zone) of rivers with gentle valley slope, Rosgen (1996) suggests that this is usually less than 2% or 0.02. Steeper channels tend to be sinuous in nature rather than actively meandering; this is particularly the case for channels with very coarse sediment (i.e. cobbles, boulders and bedrock). In summary, channel patterns are dictated by a great variety of factors; general rules can be applied regarding the transition from upland to lowland areas.

At the scale of individual channel reaches there is a greater understanding of process and the nature of change. However, whilst it is possible to describe the growth of a meander bend and the likely future migration of it, the timing of change is highly variable. Rates of channel change expressed as growth rates per year or amounts of lateral migration can mask the fact that changes can be highly stochastic in nature. Xu (1995) summarises the conditions responsible for a meandering pattern. Bank material must be quite resistant to erosion by flowing water although banks can still be eroded and retreat. Bedload should be relatively low, but a certain amount of washload should be available; both the seasonal range of water discharge and the variation coefficient of yearly flood peaks should be small so that the river is in a fill-scour equilibrium. By contrast bank material with a low resistance to erosion, a high sediment load, particularly bedload which leads to rapid aggradation, a high discharge range and flood peak variation coefficient; are responsible for the formation of wandering braided river channel patterns (Xu, 1995).

The mechanics of meander bends have been well described in terms of plan geometry (wavelength and amplitude) and the spacing of morphological features (riffles and pools) by many researchers (e.g. Leopold et al, 1964; Thompson, 1986; Thorne, 1997). The evolution of meander loops is likely to include downstream migration, increase in amplitude and eventual cutoff at the neck (Brice, 1974). Meanders tend to maintain a constant curvature but a reduced radius as they develop and can form multiple. Classic meander bends can develop into asymmetric and complex forms with new curves developing on the old ones e.g. compound meanders (Hooke and Harvey, 1983). It is equally possible that meanders are stable in planform and do not migrate. In many cases stability may be linked to local bank resistance or entrenchment of the channel, historical analysis is a good indication of channel stability. However caution should be exercised in assumptions of stability since changes in other parts of the river may destabilise channel planform e.g. a meander cutoff or channelisation (e.g. Hooke, 1995b).

5.2 Channel morphology and geometry

Channel geometry has been the subject of much research and has recently been reviewed by Park (1995). The cross sectional area and width to depth ratio are both functions of discharge; the width to depth ratio increases downstream. However the precise shape of the channel cross section is dependent on local sedimentology which has proved difficult to quantify (Richards, 1982 see also Miller and Quick, 1993).

A number of regime equations have been developed that illustrate the relationships between channel geometry and other controlling factors. Caution should be exercised when used regime equations that give average values only, if they are being used for design purposes then maximum variability for all the variables should be incorporated. Many of the equations are also limited in the range of their applicability; either in terms of bed material size or type of channel. Equations are presented here to illustrate the connectivity between channel shape, bed morphology, vegetation and discharge.

The equations in Box 5.1 are taken from Hey (1997) who presented a suite of regime equations for gravel bed rivers specifically for use in river restoration projects and engineering geomorphology. The equations were developed by Hey and Thorne (1986).

Box 1. Hey and Thornes equations

Database and range of applications:
Bankfull discharge Q: 3.9 – 424 m3 s-1
Bankfull sediment discharge (as defined by Parker et al's (1982) bedload sediment equation) Q_s: 0.001 – 14.14 kg s-1
Median bed material size D_{50}: 0.014 – 0.176 m
(D_{84} is the 84[th] percentile of the grain size distribution)
Box 1 continued
Bank material: composite, with cohesive fine sand and clay overlying gravel
Bank vegetation: Type I, 0% trees and shrubs
Type II, 1 – 5%
Type III, 5 – 50%
Type IV, >50%
Valley slope S_v : 0.00166 – 0.219
Planform: straight and meandering
Profile: riffles and pools

Bankfull width, W (reach average):

$W = 4.33Q^{0.5}$ (m)	vegetation type I	(Equation 5.4)
$W = 3.33Q^{0.5}$ (m)	vegetation type II	(Equation 5.5)
$W = 2.73Q^{0.5}$ (m)	vegetation type III	(Equation 5.6)
$W = 2.34Q^{0.5}$ (m)	vegetation type IV	(Equation 5.7)

Bankfull mean depth, d (reach average):

$D = 0.22Q^{0.37} D_{50}^{-0.11}$ (m)	vegetation types I – IV	(Equation 5.8)

Bankfull slope, S:

$S = 0.087Q^{-0.43}D_{50}^{-0.09}D_{84}^{0.84}Q_s^{0.10}$	vegetation types I – IV	(Equation 5.9)

Bankfull maximum depth, d_m (reach average):

$D_m = 0.20Q^{0.36}D_{50}^{-0.56}D_{84}^{0.35}$ (m)	vegetation types I – IV	(Equation 5.10)

Sinuosity, *p*:

$P = S_v/S$	vegetation types I – IV	(Equation 5.11)

Equations have also been developed for riffle and pool width and depths, see (Hey, 1997).

In addition to the channel cross section geometry geomorphological theory is able to predict approximate spacing of bed features such as riffles and pools. The accepted riffle spacing is between 5 and 7 times the channel width although there is a considerable spread of data around this value and the range is somewhere between 3 and 10 times the channel width (for discussion see Gregory et al, 1994 and Carling and Orr, in submission). The theoretical spacing of alternate bars is approximately equal to six times the flow width at the bed derived from the spacing of turbulent flow structures (for discussion of bedforms and turbulent flow structures see Yalin, 1992).

In all channel patterns the spacing of morphological bed features and the distribution of flow types is relatively well understood. It is the structure of flow that dictates the bed morphology that in turn drives the development of channel pattern. Thompson (1986) examined riffle-pool units and observations of associated flow structures to demonstrate the links between bedforms, flow patterns and channel change:

> "Each unit appears to be associated with a systematic pattern of secondary flows, which are able to modify the bedforms and initiate meander development. Feedback links between plan morphology, flow patterns and erosive and depositional forces within these units ensure that each stage of meander growth has a characteristic style of channel change. Consequently, meanders tend to evolve by regular cycles of increasing curvature and complexity."

Different sedimentological forms influence both channel dynamics and morphological response and necessarily play a role in channel stability (Lewin *et al,* 1988). Church and Jones (1982) describe megaforms where sediment moves through channels as a sequence of depositional zones visible as the riffle pool sequence. The corresponding flow patterns can be mapped in planform as in the schematic diagram in Figure 5.4 (after Thompson, 1986). The distribution of flow patterns is also well known for lateral cross sections, consideration of secondary flows is particularly important in bank erosion processes described in the next section. Upwelling flow at the outer margins of channel bends has been described (Thorne and Hey, 1979) where outer banks are steep (Figure 5.5 after Markham and Thorne, 1992). The strength of secondary flow circulation is dependent on flow stage and is greatest at medium discharges (Bathurst et al, 1979). The existence of a cell of reverse rotation may be dependent on the width to depth ratio of the channel; up-welling flow cells were not observed in the upper River Lune with width to depth ratio of 28 (Orr, 1996) but do exist on the main floodplain area.

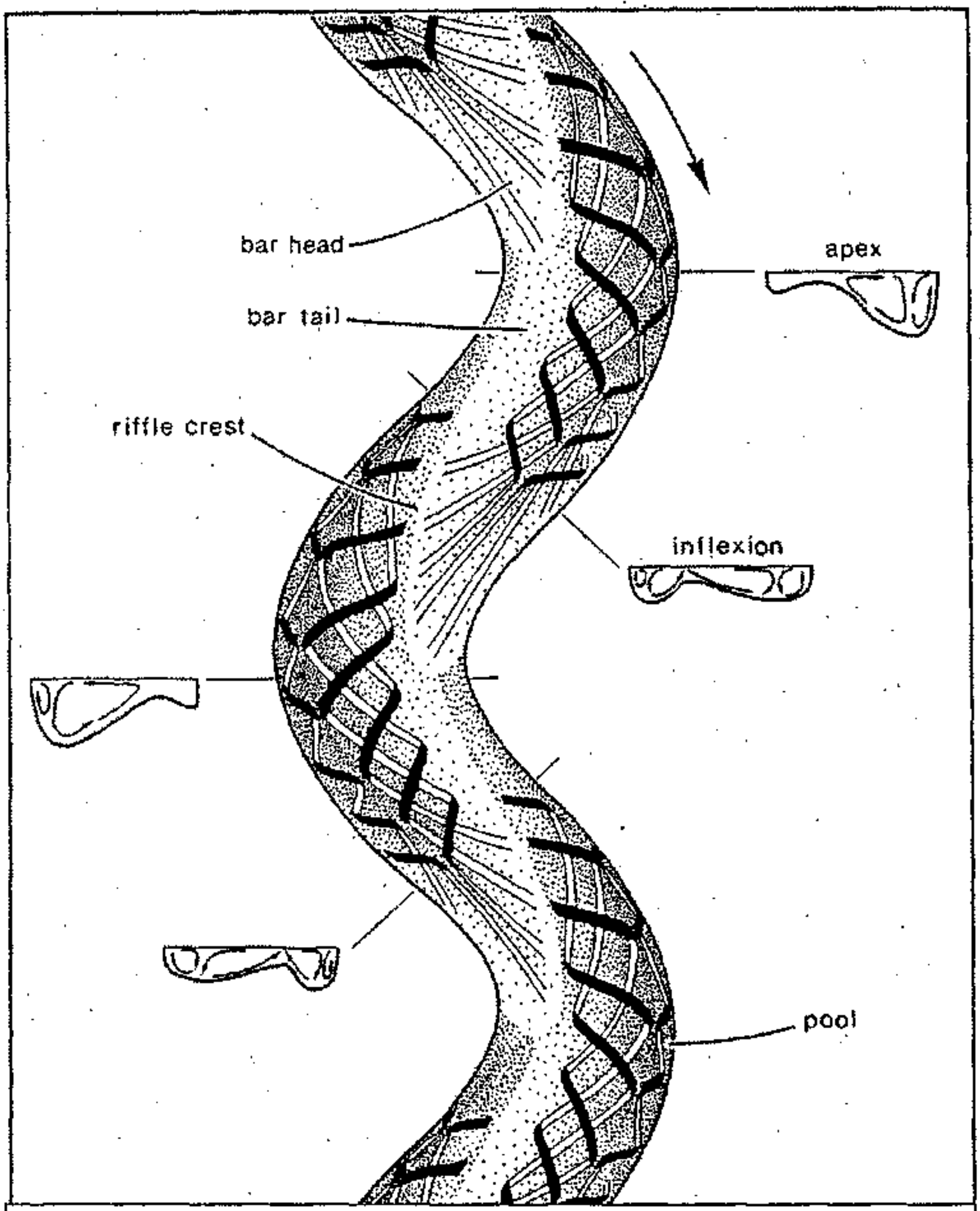


Figure 5.4 Secondary flow patterns and bed morphology

The development of velocity meters that are able to measure two and three-dimensional flows has heightened awareness of flow structures in rivers. Much of the research effort is now concentrated on linking channel morphology to the spacing of small, medium and large-scale coherent flow structures (Best, 1993; Robert et al, 1993). The relationship between flow, sediment transport and bedform development has been described in simple terms by Leeder (1983) but involves very complex relationships and feedback mechanisms; much research is still needed in this area.

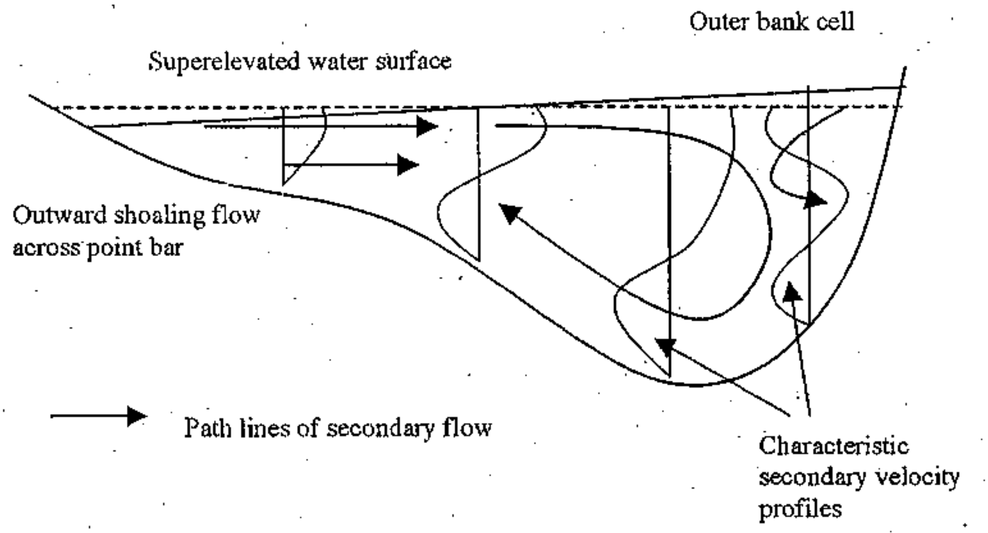


Figure 5.5 Secondary circulation at a river bend

5.3 BANK EROSION

Bank erosion is only one aspect of channel morphology and change, however it has been allocated its own section because of the high profile given to erosion in river management. Bank erosion may be a major source of sediment in many landscapes and up to 50% of the catchment sediment output (Grimshaw and Lewin, 1980) in a normal year so that the rate of bank erosion is of great importance in siltation problems. It should be noted that the amount of non-channel sources of fine sediment substantially increases in large floods. Damage from river bank erosion has been priced at $270 million per year in the U.S.A. (Lawler, 1993); figures are less for the UK, £40 million in 1980 (Newson, 1986a). The control of bank erosion is a major impetus in applications for land drainage consent received by the Environment Agency, particularly in rural areas. In many parts of Britain, floodplain land is highly valued by riparian landowners, providing the highest quality grazing and most fertile soils for cultivation. The loss of even small areas of land to erosion is often a source of major dispute; land "gained" by deposition is rarely productive for at least ten years.

The precise mechanisms for bank erosion are complex given the range of bed and bank materials, flow regimes and climatic factors operating in different river systems. Some have argued that a range of processes are responsible for erosion (e.g. Hooke, 1979; Thorne, 1982) and that some processes may dominate over others in some locations. For example undercutting (Stott, 1997) and antecedent precipitation (Hooke, 1979). However identification of dominant processes requires careful, and often problematic, monitoring. Lawler (1992) reviewed the variety of competing theories of dominant mechanisms in bank retreat and suggested three important factors to take into account: limitations of present field monitoring techniques, temporal change in bank erodibility and downstream change in bank erosion processes

Mechanisms for bank failure can be divided into two main groups; direct action by water either by river flow, sometimes referred to as corrasion, or by rainsplash and wash; the second group are mass failures dependent on mechanical properties of the sediment (Richards, 1982). Mass failures include rotational failures, caused by shearing and sliding often after heavy wetting, and tension and beam failure after undercutting by flood flows. Hooke (1979) describes erosion processes in Devon rivers as consisting of two main processes; corrasion during high flows leaving smooth banks often with turf overhangs which are usually washed away in succeeding floods. The second main process occurred when banks were thoroughly moistened and bank hydraulics were such that large blocks collapsed or slumped after the passing of flood peaks. Slumping may be related to the rate of fall of the hydrograph (Twidale, 1964). A third possible processes was identified as rotational slumping, Laury (1971) describes these failures as occurring adjacent to scour pools and producing stepped bank profiles. Bank seepage may be important; Burgi and Karaki (1971) suggest that erosion is related to the hydraulic gradient across the bank at low flows and velocity at high flows. A further mechanism for bank failure was reported by Davis and Gregory (1994) for wooded streams whereby an enclosed cavity forms through large scale seepage in the river banks, leading to slow subsidence of a section of bank aided by the existence of a coarse woody debris dam. Other important processes may include the presence of turbulent features such as circular upwellings and spiral vortices (Hooke, 1979). The modes and characteristics of bank failure have been summarised by Hey et al (1991) and are shown in Figure 5.6. Hooke (1980) describes erosion rates in Devon with mean rates between 0.08 to 1.18 m/year and a maximum rate of 2.58 m/year, rates calculated from maps generally being less than rates measured in the field. Rates of bank erosion have been shown to be related to catchment area, Hooke (1980) showed that catchment area explained 53% of the variation in mean erosion rates and 39% of the variability in maximum rates; arithmetic and logarithmic equations are shown below:

$$Y = 8.67 + 0.114A \quad (r = 0.73) \qquad (5.12)$$

$$Y = 2.45A^{0.45} \quad (r = 0.63) \qquad (5.13)$$

Where Y is the erosion rate per year in metres and A is the catchment area in Km^2. Lateral erosion rates have also been explained by the catchment size and the size of sediment at the base of the outer bank in meanders (Nanson and Hicken, 1986). It would appear that bank erosion and channel migration are essentially problems of sediment entrainment which is dependent on stream power and sediment size, where stream power is a function of discharge and slope (Nanson and Hicken, 1986).

It is generally reported that bank erosion rates are higher in the winter period in Britain (e.g. Stott, 1997) this is partly as a result of frost action and needle ice (Lawler, 1993a). Stott (1997) reports on the correlation between bank erosion rates and both fluvial activity and frost indices in central Scotland; erosion correlated most closely with frost. Needle ice formation is an important mechanism for erosion and perhaps more important in the preparatory role it plays in preparing banks for fluvial activity.

River managers are often faced with situations where bank erosion is accelerated either locally or throughout large reaches. The most widely reported factor affecting accelerated rates of erosion is the presence or absence of vegetation. Unvegetated

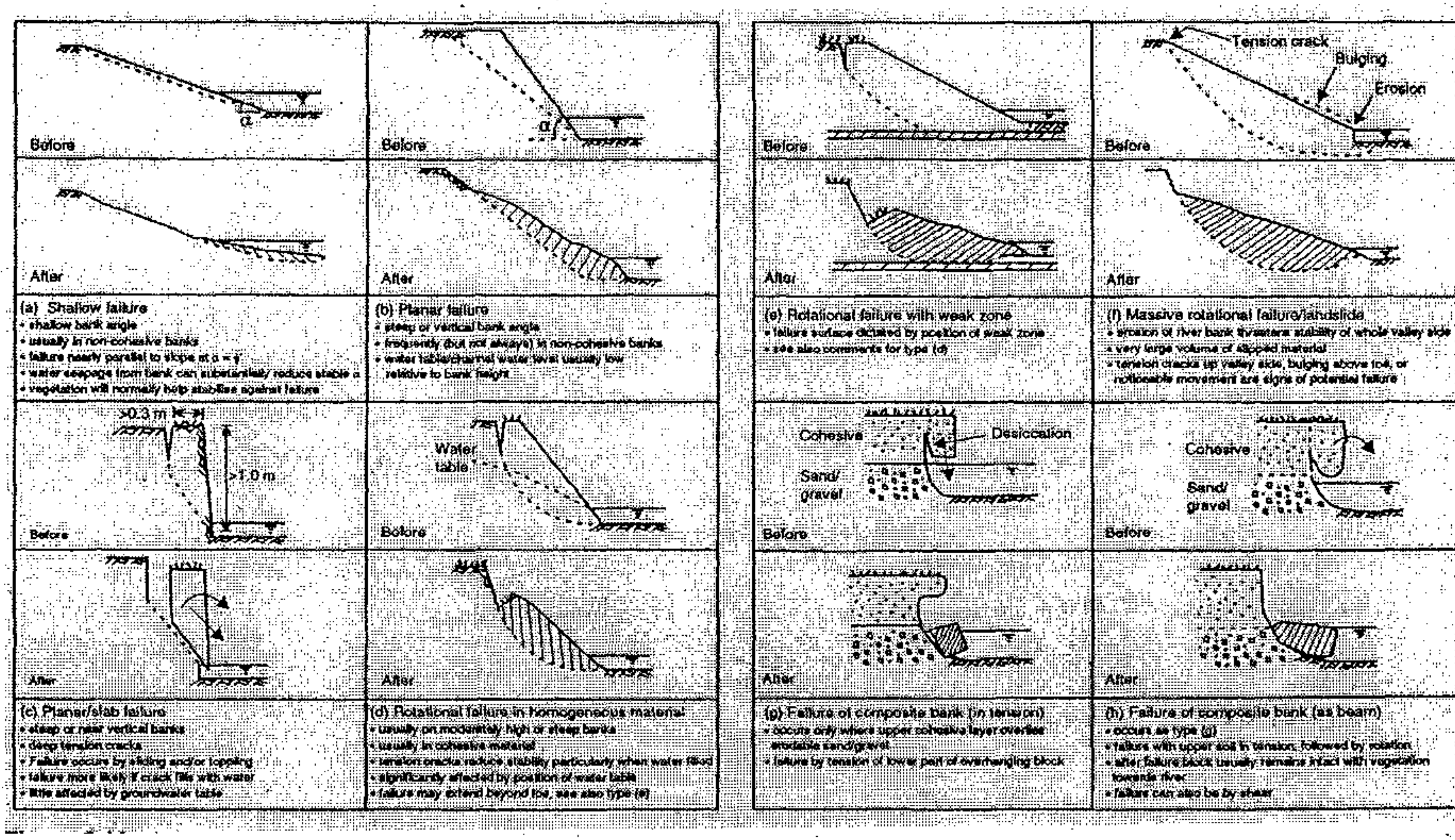


Figure 5.6 Mechanisms of bank erosion (after Hey, et al, 1991)

banks in the U.S.A. were found to be five times more likely to undergo detectable erosion than vegetated banks and thirty times more likely to undergo major erosion (Beeson and Doyle, 1995). This study looked at 748 meander bends using aerial photography and classifying banks as vegetated if they had trees or shrubs.

The effect of channel straightening on rates of bank erosion has been discussed by Brookes (1988 and 1995) where sinuosity is reduced and slope increased resulting in erosion of the bed and banks as the channel attempts to reduce its gradient and restore some stability. Forestry activities have also been reported to increase rates of bank (e.g. Murgatroyd and Ternan, 1983; Newson, 1980; Stott, 1997) Often new erosion or locally accelerated rates are the result of bank revetments which frequently serve to move the problem elsewhere (Brookes, 1988).

In order to understand and therefore manage the processes operating in a particular location it is vital to place this location in the context of the whole river catchment. The nature of British gravel bed rivers can be tentatively summarised. Sites in upland areas with steep channels are likely to have coarse bed and bank materials and a relatively straight or sinuous planform of relative stability and step-pool bed morphology. Transitional zones between upland and lowland areas may be meandering in planform either in confined floodplains or river terraces, bed and bank materials may be variable and riffle-pool bed morphology is likely. Piedmont zones with wide floodplains are likely to have a meandering planform with steep cut banks. Bank erosion mechanisms are likely to include undercutting, block failure and slumping; lateral migration may be rapid. At all locations within the catchment locally high rates of sediment supply or incohesive bank material, may produce braided patterns or divided channels, this is particularly likely in transitional zones.

5.4 GEOMORPHIC THRESHOLDS

In the long-term upland British rivers are adjusting to the last glaciation, northwest rivers were initiated after the last glaciation between 18 ka BP and 15.5 ka BP; major regime changes are likely to have occurred following land clearances about 2.5 ka BP. Whilst the early Holocene (10 ka BP) saw the stabilisation of an unstable landscape, the activities of man (c. 900 BP) caused a partial de-stabilisation in the uplands (see Section 3, Figure 3.1). Following the late Pleistocene ice melt, sediment was fed into proglacial river systems (melt water channels). Later incision of these sediments has left a legacy of fluvioglacial terraces (Harvey, 1997) which can be observed in the Lune valley. The low level of fluvial activity in the early Holocene was followed by increased activity in the late Holocene (Harvey, 1985a). These changes follow climatic deterioration from the, mid–Holocene thermal optimum (c. 6 ka BP) and may have been a direct response to climate change or climate induced vegetation change (Harvey, 1997).

Late Holocene fluvial change is the subject of some debate and has been associated with climate change as flood sequences in north east England (Rumsby and Macklin, 1994) and also to sediment supply stressing the human impacts (Harvey et al 1981 and Hooke et al, 1990). Harvey (1997) in his description of the fluvial geomorphology of northwest England suggests that both climate and human influences are important:

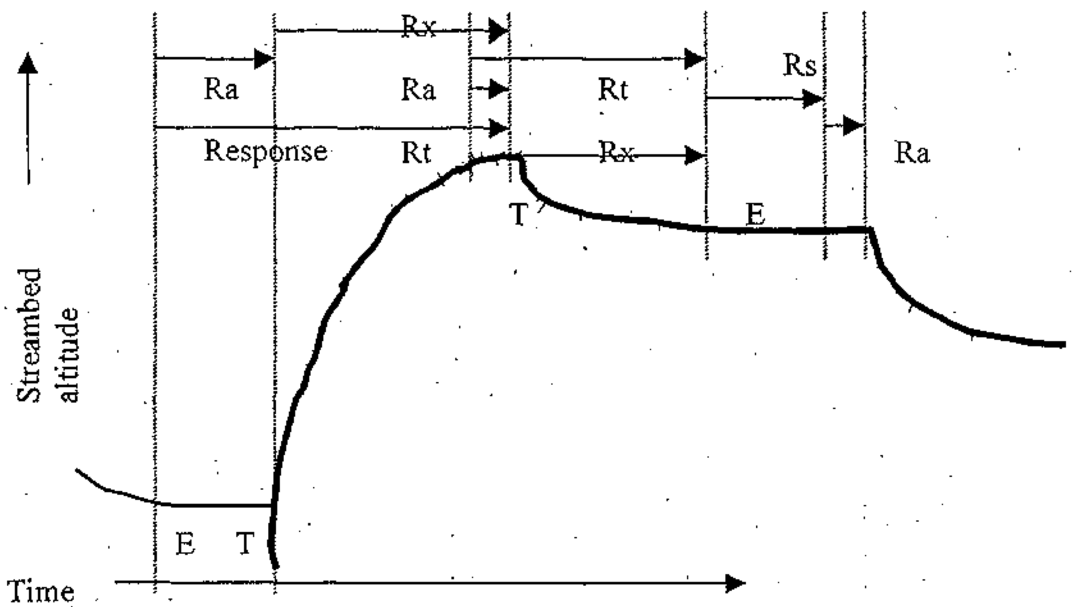
> "In upland sites where coupling between hillslope sediment sources and the channel system is strong (Harvey, 1992a, 1994), the impact of

> variations in sediment is high: hence the potential for response to human-induced erosion. In piedmont reaches (sensu Newson, 1981) variations in stream power may be more important, therefore these larger rivers may be more responsive to a climatically induced flood signal."

Harvey (1997) summarises that interactions between the two factors may explain the geographical variations between upland and lowland, river response. Climatic variability is discussed in Section 2, this section addresses the importance of climatic and human induced changes for the crossing of geomorphic thresholds.

A long-term view of river development is essential to understanding landform development in order that the dominant processes may be discovered. The process of river channel adjustment to new environmental constraints is not immediate and may take several decades to complete. River channel change also has a spatial context, in that upstream changes may have effects which work their way downstream with a temporal lag between cause and effect especially in the middle and lower reaches of river basins (Lewin *et al*, 1988). For a general discussion of time lags refer to Allen, (1974). Thus many rivers are adjusting rather than being in an equilibrium state some of the causes of adjustment have been described by Lewin *et al* (1988) as the response to, or recovery from large or rare floods and changes in flood magnitude and frequency. These may be influencing channel capacity through: climate change; changes in landuse, which increase or decrease, flood magnitude; changes imposed progressively by river regulation from upstream; changes resulting from declining floodplain storage. Over long periods of time these may be caused by changes in agriculture and settlement. Over shorter periods channelisation and embankment may increase the stream power and have a (relatively) sudden destabilising effect on channels (e.g. Leeks *et al*, 1988). Changes may also result from sediment supply fluctuation e.g. increased sediment yield from intensified agriculture. The adjustment of river channels to a new regime following the crossing of different geomorphic thresholds can occur over a great variety of temporal scales. A conceptual framework for the analysis of periods of equilibrium and thresholds of change is given in Bull (1991) and described briefly below. The plot shown in Figure 5.5 uses the concept of response time (Allan, 1974) to illustrate the threshold-equilibrium relationship. Where T and E represent threshold and equilibrium respectively, R_t is the response time, R_a the reaction time, R_x the relaxation time, P_s is the time of persistence of the new equilibrium conditions. Response time is the sum of reaction and relaxation time; this is a useful concept because many thresholds may have zero persistence times. The response time concept may be used as a measure of the sensitivity of a system to change.

Figure 5.7 Threshold-equilibrium plot (after Bull, 1991)



Regime changes occur naturally, for example in response to large floods, the sequence of flood events is also believed to be important in the crossing of geomorphic thresholds (Beven, 1981). One or more large flood events are thought to be responsible for a change in channel behaviour since the 1930s on the River Bollin in Cheshire (Mosley, 1975) which caused an equilibrium threshold to be crossed. It is important to realise that the crossing of geomorphic or hydrologic thresholds may occur some time after the progressive change in, for example land use, which can make the identification of the cause of instability very difficult. Changes in flood frequency and magnitude as a result of climate change will have obvious immediate effects however the changes in the channel morphology as a result are less easy to observe or predict. Harvey (1991) observed in the Howgill Fells that channels became braided in response to flood events and the change in sediment supply. A new channel morphology as a result of flooding may become the new regime of a channel or a previous equilibrium may eventually be reached and the channel morphology reinstated. Other research further downstream in the Lune catchment (Thompson, 1984) attributed major channel activity and change to the process of meander development and not in large part to changes in flood frequency.

5.5 INSTABILITY AND READJUSTMENT

Instability occurs in rivers where there is an imbalance between sediment supply and the ability of rivers to transport it. In natural rivers unstable channels are usually found in the headwaters. Hey (1990) suggests that regime conditions prevail in downstream reaches although regime theory may not be the most appropriate way of classifying rivers. In general however lowland rivers do not exhibit the same degree of change and unless major changes occur to the discharge or sediment regime these rivers tend to maintain, an average channel geometry, although channel migration can be present. The natural river channel creates a geometry that will accommodate a wide range of flows such that it is in harmony with its, sediment and discharge regime. Any change in either sediment supply or discharge will have an effect on channel morphology.

Activity by man over the recent past (hundreds of years) has lead to long-term progressive changes in river morphology; for example it is likely that all lowland floodplain rivers in Britain once had braided channels prior to deforestation. Much of the change in runoff and sediment loads is so gradual that rivers have time to adjust morphologically without obvious large-scale instability. In many cases this has lead to rivers being described as being in dynamic equilibrium, particularly large rivers (hundreds of km). This is not necessarily the case in small river catchments where large floods can lead to rapid destabilisation. This is probably because the intense storms that generate major changes in small catchments rarely occur over large enough areas to produce similarly catastrophic floods in large catchments. River morphology has been shown to relate closely to short-term flood events but in the longer-term is more closely related to the stage of development of meanders (e.g. Thompson, 1984). Channel sinuosity results from the shape of the hydrograph, the amount and type of sediments and the valley slope. Meander wavelength is a geometric parameter that is closely related to the discharge, such that meander wavelength is likely to increase in response to increased discharges.

Land drainage in many cases may increase discharge so that the channel is required to contain a greater quantity of water during floods whilst at the same time the channel length may be reduced as a result of channelisation. It has been argued that human impacts on rivers are our greatest cultural influence on the natural environment. Many different scales of effects may be acting on a river system both temporally and spatially, the response time and recovery time of these effects is complex and often not well understood.

Our current understanding of fluvial systems does not allow for the prediction of the type or magnitude of geomorphic response to a given perturbation although it is possible to predict a variety of possible responses (Miller and Ritter, 1996). We do know that any given reach may respond differently, at different times, to an event of similar magnitude (e.g. Newson, 1980; Beven, 1981). However, evidence of morphological instability is usually obvious and in small catchments with a well-known land use history, rainfall and discharge gauging stations, cause can often be assigned. Identification of instability becomes more problematic with increasing catchment size.

Readjustment to changing conditions may take hundreds or thousands of years although climatic change occurs with such frequency that it could be argued that fluvial systems are continuously adjusting. The impacts of climatic change and other geomorphic driving mechanisms should therefore be considered within appropriate conceptual and temporal frameworks. There has been much debate about whether geological change is slow and gradual and "uniformitarian" or whether change occurs as a result of active periods or catastrophic action (Werrity, 1993 and 1997). The same discussion has prevailed in fluvial geomorphology and whether geomorphic effectiveness may best be described by the series of medium sized floods or by rare and catastrophic events. Werrity (1997) suggests that the geomorphic effectiveness is at least in part defined by location within a drainage system. Steep upland sites with relatively confined channels may undergo dramatic geomorphic change as a result of rare events (Carling, 1986) whereas lowland or piedmont sites may be more likely to undergo vertical accretion on nearby floodplains or progressive meander bend development (Thompson, 1984).

WK

Rivers may naturally respond rapidly to alternating periods of high and low flood activity for example, the lower Hunter River responded to increased flood frequencies by straightening its channel (Erskine, 1992). Upland streams in the Howgill, Fells were shown to change to a braided form in response to a large flood and then to return to the previous channel form within five years (Harvey, 1991). River channel adjustment to meander growth and cut-offs, has been the subject of considerable research (e.g. Brice, 1974; Ferguson, 1977; Thompson, 1985; Hooke, 1995). Once meanders have cut-off, the terminal result of progressive bank erosion usually during peak flow events, the straightened channel is likely to undergo rapid channel widening and sedimentation (Hooke, 1995). Observations from the Rivers Bollin and Dane in northwest England (Hooke, 1995) showed that channel adjustment was mainly by formation of multiple riffles and bars, producing a variable morphology in the first 2-4 years. In one case progressive steepening and bank erosion was initiated upstream but most erosion effects were local. Hooke (1995) concludes that major adjustment in these active gravel bed streams may be completed within 6-12 years.

The impacts of man on fluvial systems has long been recognised but the extent and nature of changes both spatial and temporal, of river engineering were hilighted by Brookes et al (1983) and Brookes (1985, 1986, 1987). River channelisation in particular had been seen as a necessary step to drain agricultural land, provide flood conveyancing and to protect developments (e.g. railways and roads). It was also believed that adequate bank revetments would protect from any subsequent erosion (Ferguson, 1981). Although the appropriate information for channel design was often available, monetary considerations and practical problems have historically led to the construction of inappropriate and unsustainable channels. The cost and long-term commitment to extensive maintenance of many engineering schemes was generally not considered at the planning stage.

It has been observed in nature that rivers may have specific reaches that are particularly unstable, these may be interspersed with apparently stable sections (e.g. Gilvear and Winterbottom, 1992). Reaches that are inherently unstable may continue to be dynamic despite attempts by man to control and contain them. In cases where engineers have been "successful" in controlling a reach the instability is invariably transferred to another location (Brookes, 1988). Channelisation, by reducing sinuosity, increases channel slope and consequently, stream power. Without bed-check weirs erosion is inevitable, either of bed or banks and in many cases leads to aggradation downstream and propagating knickpoints or headcutting upstream; in some cases both may occur as in the upper River Lune. In 1973 a 2.25 km section of the River Lune was channelised with a reduction in length to 1.6 km despite bed checks the section almost immediately began to erode. A report in 1993 (Fraser, 1993) identified extensive erosion of the bed and banks which despite major revetments continues to date. In the early 1990s it was observed that some natural recovery was taking place with regularly spaced riffles throughout the reach. In 1998 bank erosion is still in evidence but areas of previously eroded banks have re-vegetated however since about 1993 instability upstream has been observed (Brookes, 1988). A distinct set of propagating knickpoints is in evidence immediate upstream of the channelised reach, cut into the bedrock. A confined meander upstream, which had been previously developing slowly, began to erode a large bluff in 1993 (Orr, 1996). Considerable bank revetments have been constructed on the meandering section downstream which have regularly been maintained and have largely been deemed unsuccessful. This area had previously been an important salmonid spawning area; rapid bank erosion and gravel accretion may have contributed to the loss of this resource.

5.5.1 ASSESSMENT OF GEOMORPHIC STABILITY

The growth of fluvial geomorphology since the publication of "Fluvial Processes in Geomorphology" by Leopold, Wolman and Miller in 1964 has ensured a place for the discipline within river management. Although a formal institution has not been established in Britain, the water industry has encouraged the development of applied fluvial geomorphology, as a result many "geomorphological tools" have been developed to improve management and to support ideas of sustainability. Analysis of channel change using maps, aerial photographs and plans has long been in the domain of the fluvial geomorphologist. More recently the use of topographic surveys, fluvial audits, river reconnaissance and fluvial geomorphic mapping have become widely used. Some attempts have been made to make the subjective techniques employed by field geomorphologists more quantifiable a process described as "demystifying". Methods of spatial analysis and field data collection will be discussed below.

5.5.2 MAP TECHNIQUES

The use of historical sources to investigate changes in river channels has been central to many studies. Ordnance Survey maps allow an accurate record of change for most rivers in the British Isles for the last 150 years. In many locations earlier maps may be available (estate records, local plans) although accuracy may be a problem. Aerial photographs may exist for a variety of dates after 1900. Data derived from maps is cheap and easily accessible and although problems may arise in the detailed measurement of, for example, bank erosion; these sources are invaluable in detected river reaches which are essentially stable in the medium-term or those that are very dynamic. Historical sources can also be used to date engineering works and deliberate channel modifications. Historical data are important in the prediction of likely future channel changes since an understanding of the rate and location of change will compliment contemporary observations and make predictions more valid (Hooke and Redmond, 1989). Data make be taken directly from Ordnance Survey maps and aerial photographs and digitised at regular intervals, both banks may be traced and in channel deposits of gravel accumulations. This derived data may then be subjected to quantitative analysis; it is recommended that channel widths be depicted as a least a few mm in order for quantitative analysis to be valid (Hooke and Redmond, 1989).

5.6 CHANNEL CHANGES IN THE RIVER LUNE

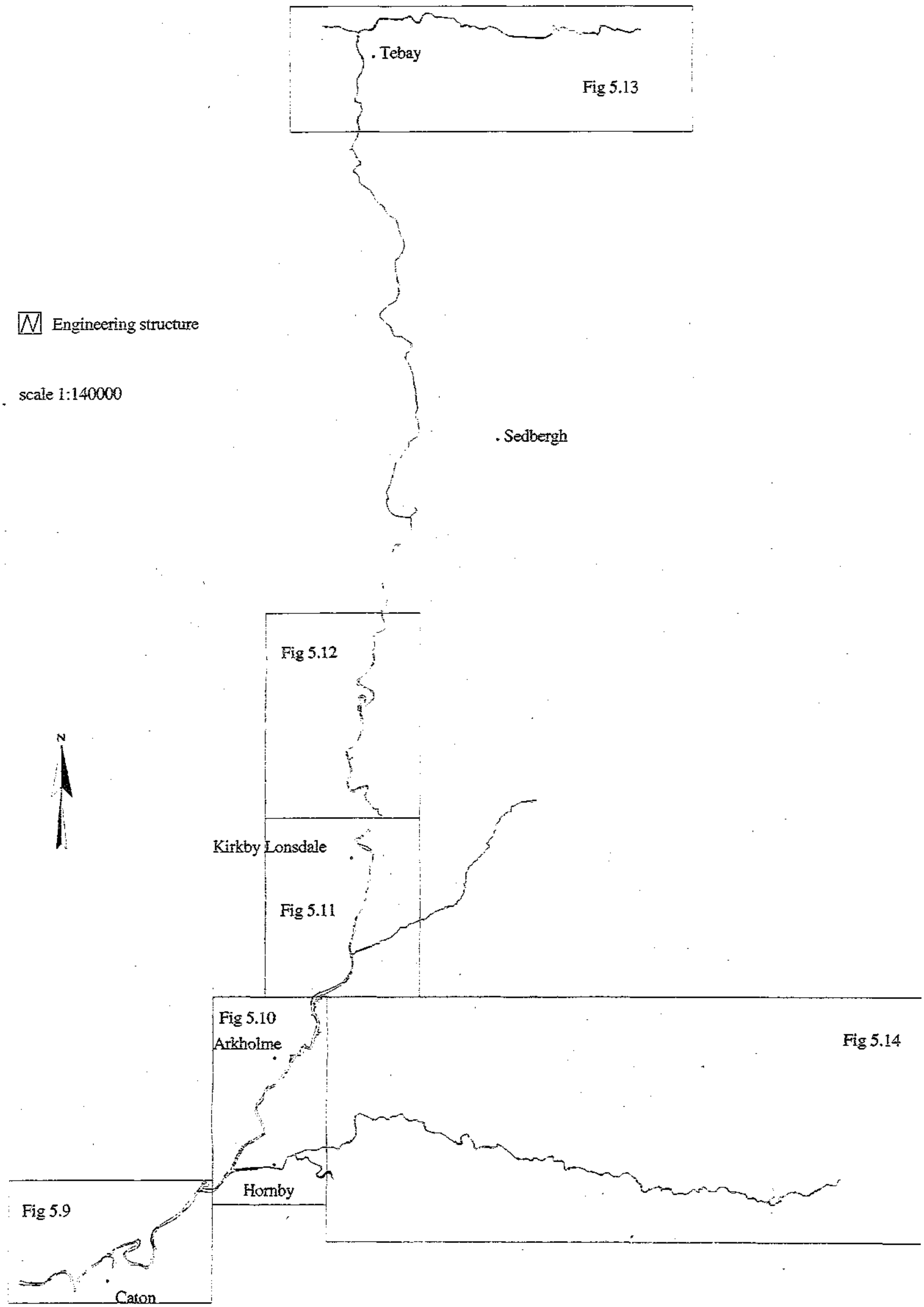
5.6.1 FIELD TECHNIQUES

Geomorphological reconnaissance surveys based on observation and interpretation may be the only source of relevant geomorphological data in many projects. Geomorphologists have become more involved in river management as more projects have been set up to 'design with nature' (Downs and Thorne, 1996). Field surveys are necessary since process-response feedback mechanisms are required up and downstream of sites. There are alternatives e. g. monitoring and modelling however time and money can often restrict monitoring. Practically applicable geomorphological models are still limited to one dimension and largely straight channels and predictions that might be made from historical data assume constant drainage basin controls.

Early reconnaissance started with Kellerhals *et al* (1976) after which various schemes have been devised to cover site, reach and catchment scales e. g. Downs and Brookes (1994), NRA (1993), Simon *et al* (1989) and Thorne and Easton (1994). It is essential to identify the current geomorphological status of a river and to predict it's future development with or without engineering intervention. Stream reconnaissance represents the only viable basis for the collection of data and information to support such predictions. Reconnaissance surveys can be multi-functional and have been used for: engineering and geomorphological analysis, stable channel design, assessment, modelling and control of bank retreat, to define the relationship between geomorphology and riparian ecology and also as a statutory requirement (Downs and Thorne, 1996). There are however limitations in the use of reconnaissance surveys, they may indicate the effects of channel forming flows but cannot answer all questions concerning process-form interactions. There is also the possibility in making future predictions that a catastrophic flood will produce new trends and patterns of change. Advantages of stream reconnaissance surveys are that they are a coherent way of collecting field data, which can be easily integrated with the multidisciplinary field of river management.

A complete survey of the main river of the Lune was conducted in 1996 together with the tributaries of the River Wenning, part of the Hindburn, Leck Beck and Birk Beck; data were added to a Geographic Information System (GIS). The main river between Kirkby Lonsdale and the Crook of Lune was resurveyed in 1997 to check the GIS output and to map any more recent erosion. The survey was principally to assess the extent of engineering work as an indicator of past erosion and to map any recent severe bank erosion. Minor erosion was not included in the mapping exercise. In addition the nature of the bed morphology and bank profiles were recorded. The physical form survey was based on the EA's River Habitat Survey (RHS) in terms of the definition of features. As the main river is approximately 70 km in length it was impractical to undertake a complete geomorphic mapping exercise, instead the river was divided into individual reaches of varying length based on geology, valley shape and floodplain extent. For each reach the number of important features was recorded and an assessment made of the physical condition and habitat value of the channel and its immediate riparian zone. The objective of the fieldwork was to investigate the extent and cause of erosion within the catchment and to assess the degree to which it should be managed in the future. The EA is a multi-functional organisation and as such issues relating to flood defence cannot be made in isolation. To aid decision making, and in the interests of integrated catchment management, the fieldwork incorporated enough information to determine channel typologies which take account of geomorphic stability and habitat value. Each reach is given a description highlighting primary processes and management recommendations and, combined with historical evidence is presented in the form of channel typologies in section 5.63.

The map in Figure 5.8 locates the following detailed diagrams of engineering structures (Figures 5.9 to 5.14) for the length of the Rivers Lune, Wenning, part of the Hindburn, Birk Beck and Leck Beck. It was not possible to survey every tributary of the Lune during the time of this project however it would be a relatively simple task for future surveys to be added to the existing GIS database. Detailed maps are not presented here for those reaches which are relatively free of engineering works and revetments (i. e. The Lune Gorge between Roundthwaite and Killington). Throughout the surveyed area 12% of the banks are engineered in some way and 7% are severely eroding. The Lune between Kirkby Lonsdale and the Crook of Lune (figures 5.9 to 5.11) is the most intensively engineered as this is the reach with the broadest floodplain and hence most likely to exhibit lateral channel migration and high rates of bank erosion. Much of the bank revetment work is located on the outer bank of meander bends which are most likely to erode, however there is also a high degree of revetment work on straight sections that are not at a high risk of fluvial erosion. This work appears to be largely a response to bank erosion and collapse through grazing pressure, i.e. where bank vegetation consists almost entirely of close cropped grass, the bank is weak and very susceptible to accelerated erosion from fluvial activity. There are a number of locations where groynes have been built and in many cases are aggravating erosion problems. An exception to this are the groynes built specifically to control erosion on the Caton meander (see features 253 to 256 on Figure 5.9). These stub or spur groynes have been carefully spaced in keeping with the hydraulics of flow operating in this reach and are largely successful, however erosion is evident and appears to be related to grazing pressure and the associated lack of bank vegetation. Most of the other in-river structures have been built by fishing clubs and have not been hydraulically designed, in most cases they are linked with severe erosion and in some cases catastrophic erosion. The only locations where these groynes are not linked with accelerated bank erosion are in situations where the bank is densely wooded. This is not necessarily an assurance that erosion will not occur in the future, dense vegetation has the effect of slowing down the rate of erosion but not entirely removing its potential initiation. Many of the existing revetments are in a dilapidated state and there are a number of examples of tipping on top of existing revetments. Such activity hinders the growth of vegetation which may establish if grazing is reduced and in the long-term adds to the instability of the bank. There are a number of locations that are historically unstable and are discussed in more detail in the next section but generally the Lune is relatively stable in its planform and the major cause of erosion appears to be localised overgrazing of its banks. The evidence for this finding is derived in part from the observation that much of the more recent revetment work is in locations that are not particularly prone to fluvial scour and erosion (i.e. straight sections). Stronger evidence is the profile of the banks, composite banks have been closely related to the activity of grazing animals. The existing vegetation along much of the lower Lune is insufficient to provide bank strength and although the extent of severe erosion (Figure 5.15) is limited to about 20% of the banks in this reach, much of the remaining bank length is also eroding to some degree. Much greater stability is observed where stock proof fencing prevents access to the banks and a good stand of tall herbs has been allowed to develop, continued stock exclusion will very likely lead to the establishment of shrubs and trees. The most stable banks on the Lune are those with adjacent dense woodland, in some cases the channel is hard up against the terrace walls and bedrock, adding to the stability in these reaches.



Tebay
Fig 5.13
Engineering structure
scale 1:140000
Sedbergh
Fig 5.12
N
Kirkby Lonsdale
Fig 5.11
Fig 5.10
Arkholme
Fig 5.14
Hornby
Fig 5.9
Caton

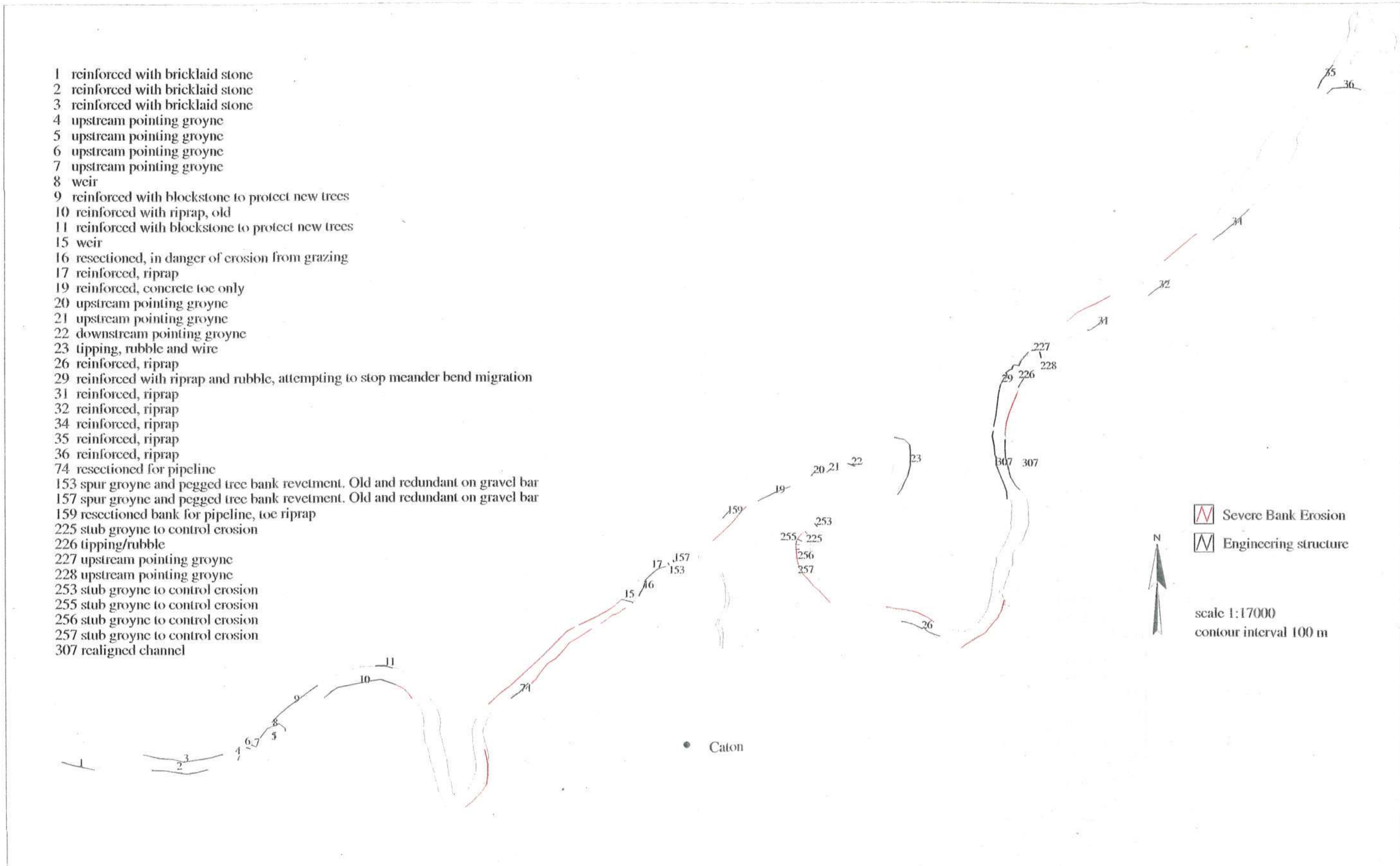


Figure 5.9 Distribution of engineering structures

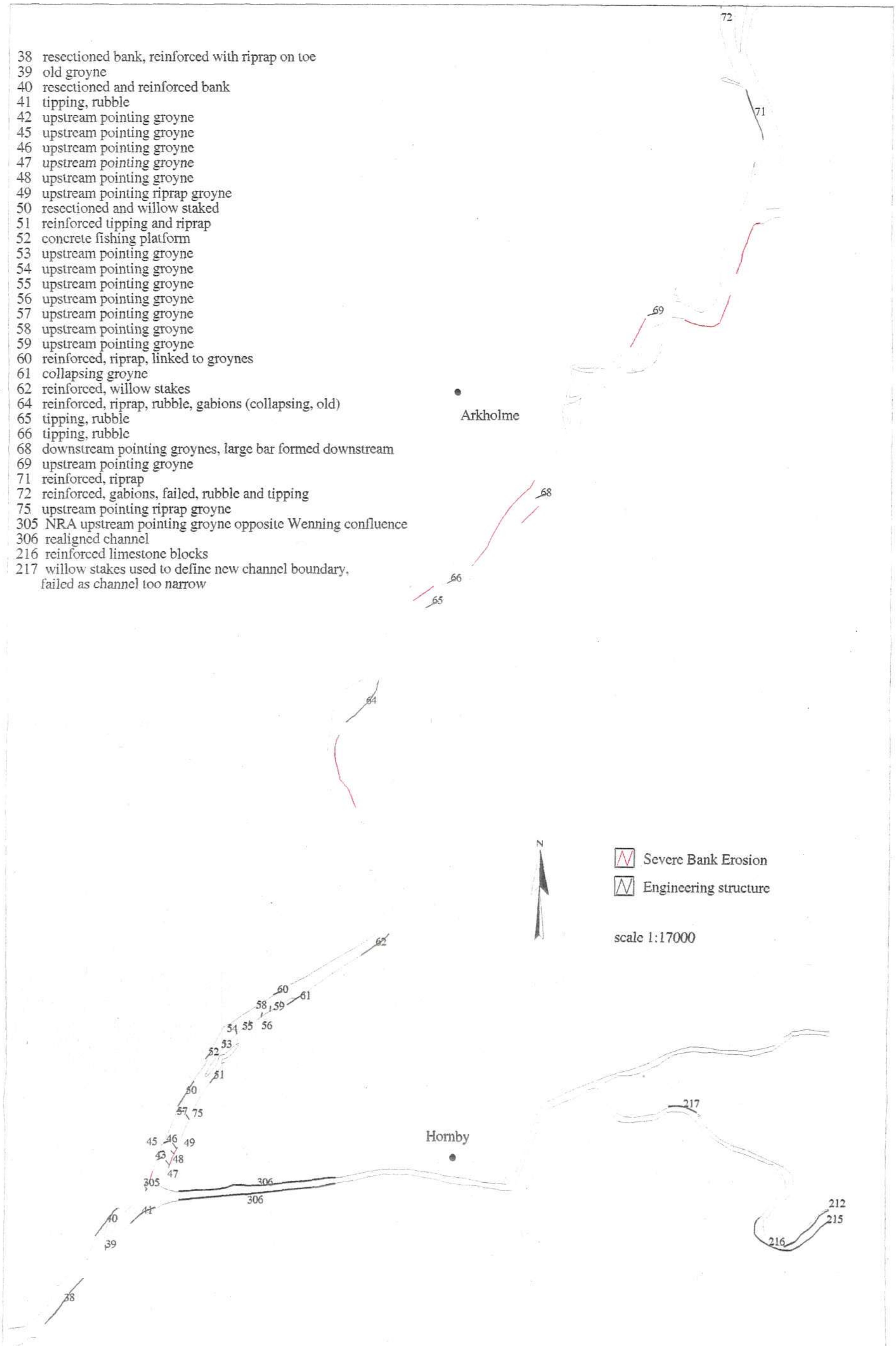


Figure 5.10 Distribution of engineering structures

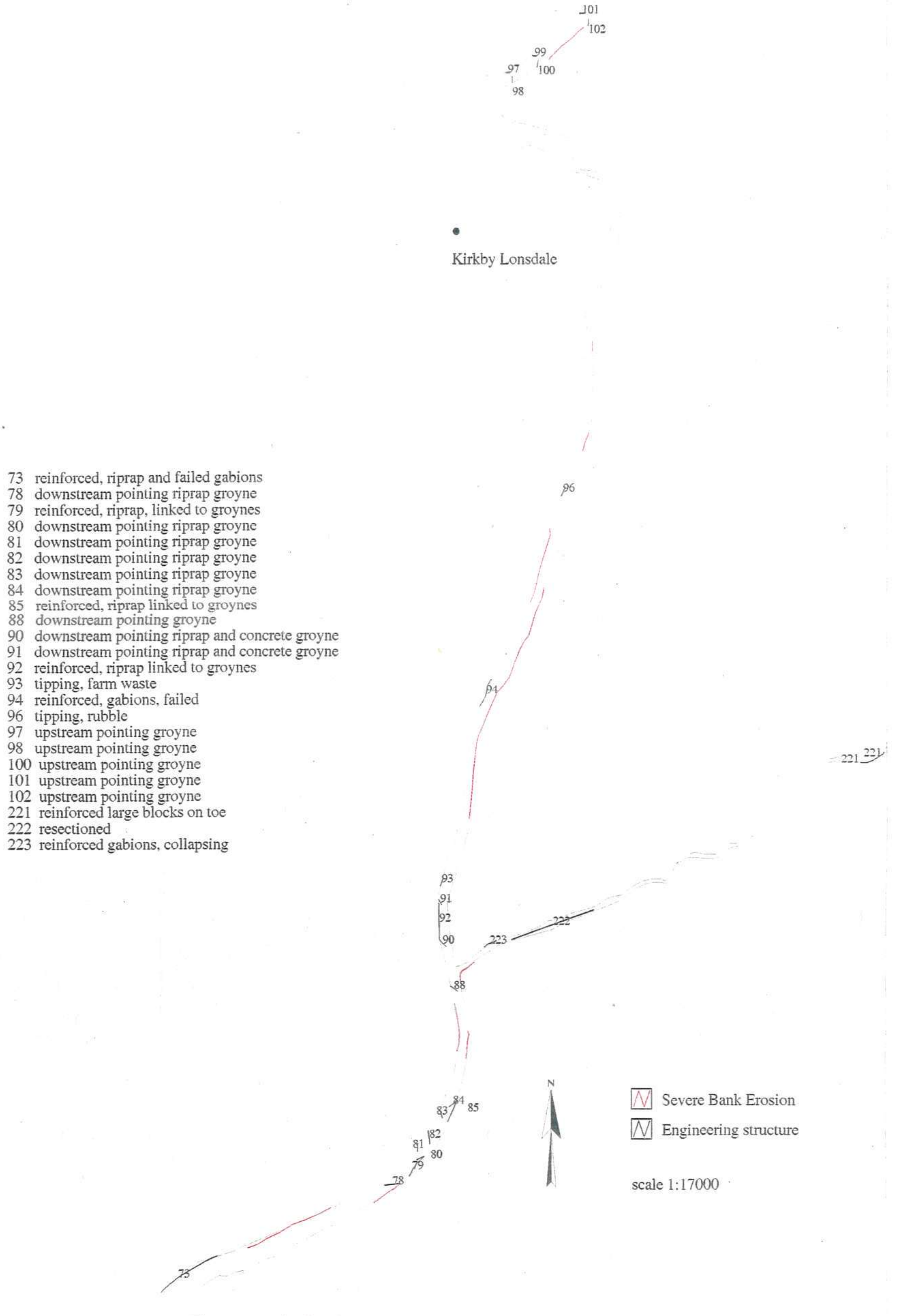


Figure 5.11 Distribution of engineering structures

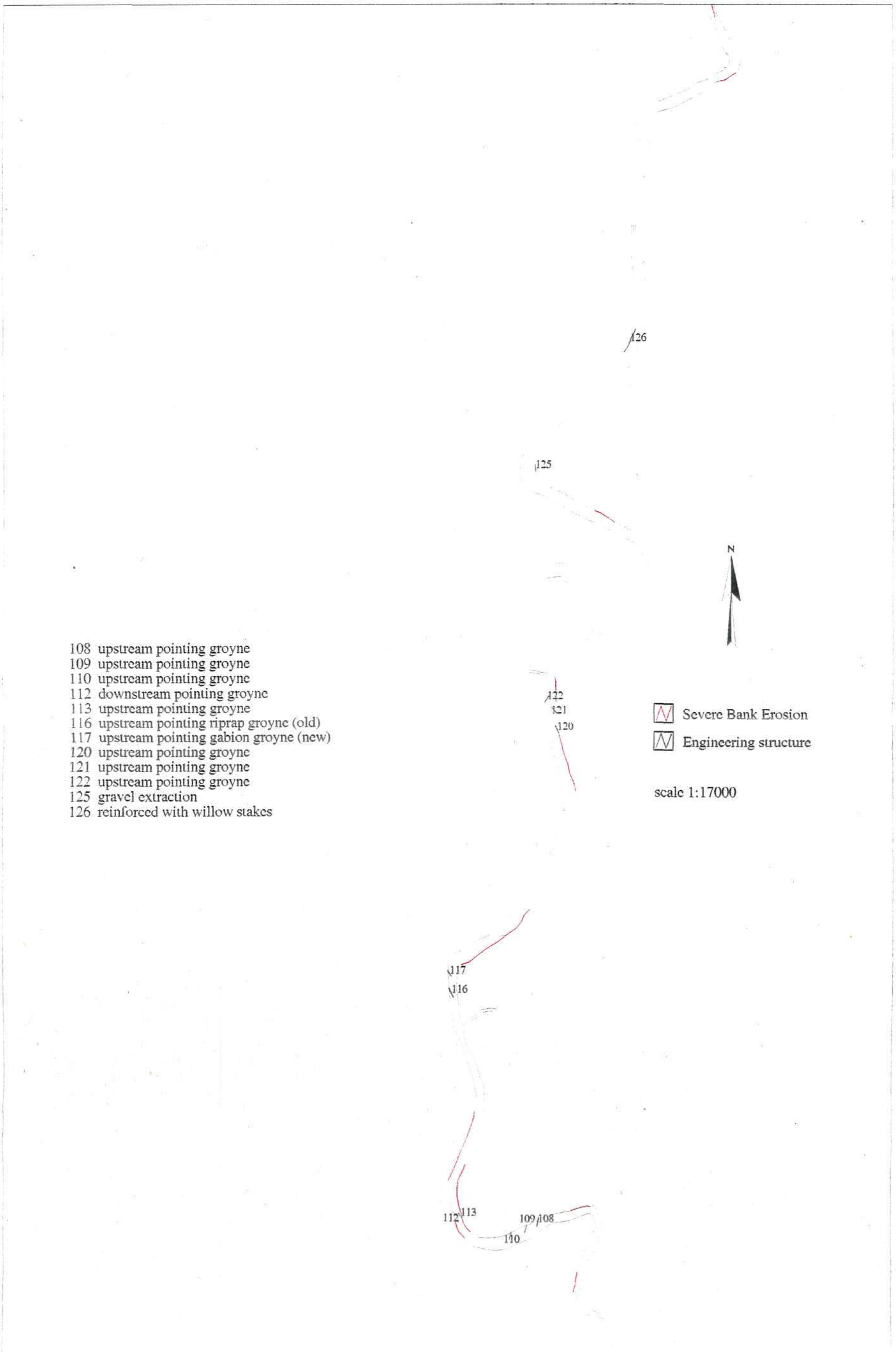
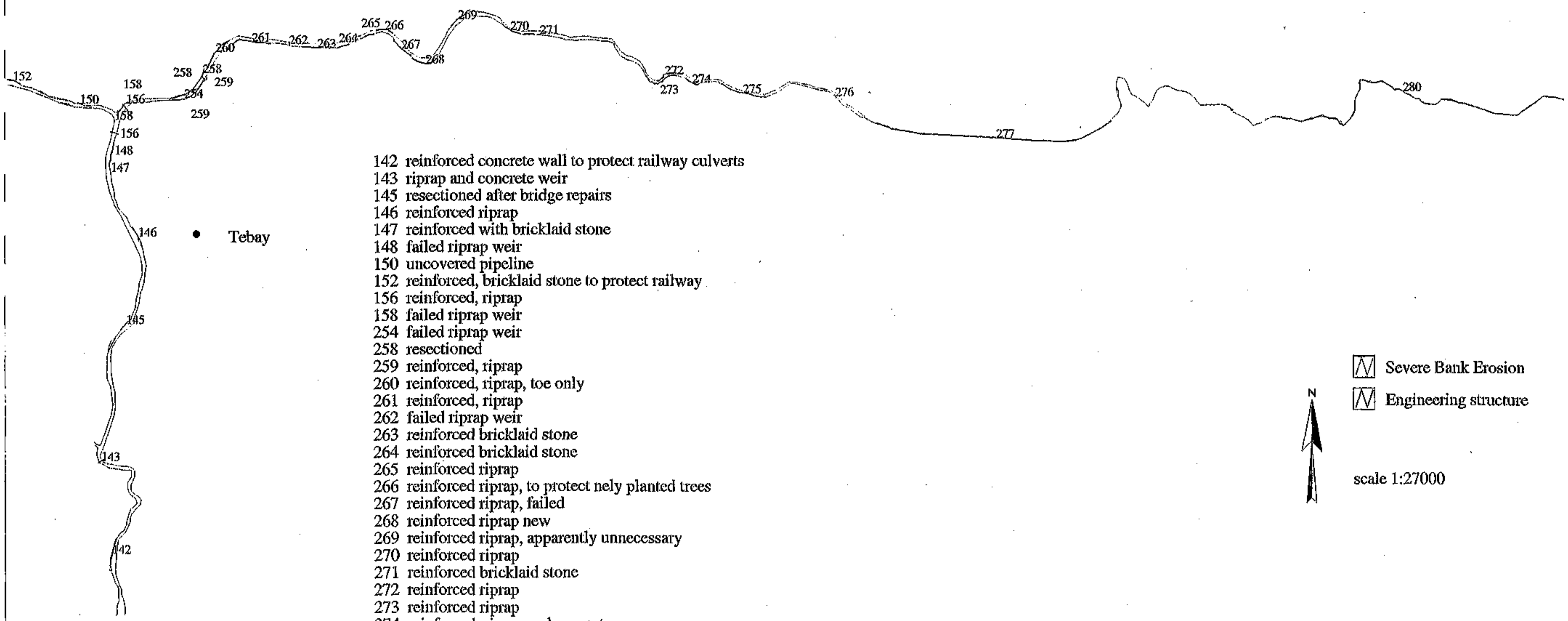


Figure 5.12 Distribution of engineering structures



142 reinforced concrete wall to protect railway culverts
143 riprap and concrete weir
145 resectioned after bridge repairs
146 reinforced riprap
147 reinforced with bricklaid stone
148 failed riprap weir
150 uncovered pipeline
152 reinforced, bricklaid stone to protect railway
156 reinforced, riprap
158 failed riprap weir
254 failed riprap weir
258 resectioned
259 reinforced, riprap
260 reinforced, riprap, toe only
261 reinforced, riprap
262 failed riprap weir
263 reinforced bricklaid stone
264 reinforced bricklaid stone
265 reinforced riprap
266 reinforced riprap, to protect nely planted trees
267 reinforced riprap, failed
268 reinforced riprap new
269 reinforced riprap, apparently unnecessary
270 reinforced riprap
271 reinforced bricklaid stone
272 reinforced riprap
273 reinforced riprap
274 reinforced, riprap and concrete
275 resectioned and riprap
276 reinforced riprap, failed
277 resectioned channel, reinforced gabion banks –will always require maintainance
280 resectioned

Figure 5.13 Distribution of engineering structures

161 tipping on point bar
162 concrete and riprap weir
165 reinforced gabions
166 reinforced limestoone blocks and sheet piling
168 reinforced riprap toe
169 resectioned
171 bricklaid stone wall
172 bricklaid stone wall
173 reinforced, stone pitching
175 riprap
176 resectioned bank, reinforced with river gravels to support new track,likely to fail
177 reinforced, bricklaid stone
179 wood piling
181 concrete weir
182 concrete weir
183 riprap
184 reinforced bricklaid stone
185 blockstone weir, old and damaged, partly operative
186 blockstone weir, old and damaged, partly operative
187 riprap
188 gabion and concrete weir
189 gabion and concrete weir
190 riprap
191 blockstone and cobble weir
192 wood and cobble low weir
193 reinforced bricklaid stone
194 reinforced bricklaid stone
196 embankment, vegetated river gravel
197 low cobble weir
198 reinforced wood piling
199 eroding cliff stabilised with willow stake

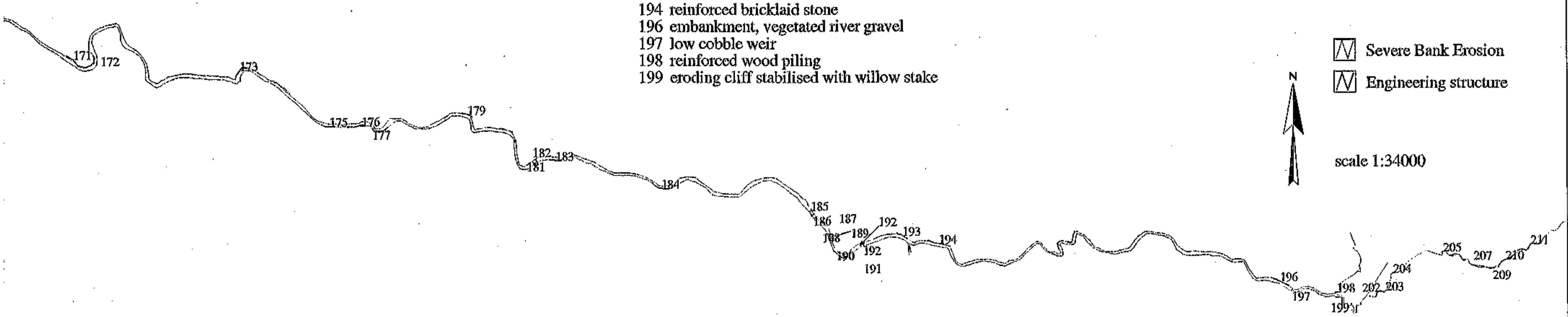


Figure 5.14 Distribution of engineering structures on the River Wenning

12 River Lune LB eroding cliff, overgrazed, unfenced, no trees
13 River Lune LB composite bank profile, overgrazed, poached, isolated trees
14 River Lune RB eroding cliff, slumped material on toe, overgrazed, unfenced, no trees
18 River Lune LB composite bank profile, overgrazed, unfenced, no trees
25 River Lune RB composite bank profile, overgrazed, unfenced, no trees
27 River Lune LB composite bank profile, overgrazed, unfenced, no trees
27 River Lune LB eroding cliff and slumped material on toe
28 River Lune LB eroding bank
30 River Lune ER eroding cliff very high
33 River Lune RB eroding bank
44 River Lune RB eroding cliff, linked to groynes
63 River Lune LB composite bank profile, overgrazed and unfenced
67 River Lune RB eroding overgrazed bank
70 River Lune LB eroding bank
76 River Lune RB composite bank profile, overgrazed and unfenced
77 River Lune LB erosion from outwash around groyne
86 River Lune LB eroding cliff, linked to groynes
87 River Lune RB eroding cliff, linked to groynes
89 River Lune LB eroding bank
95 River Lune LB composite bank profile, overgrazed, unfenced and poached
104 River Lune LB composite bank profile, erosion linked to groynes and grazing
105 River Lune LB eroding cliff
106 River Lune LB eroding cliff
107 River Lune RB eroding bank
111 River Lune RB eroding cliff, linked to groynes and fallen tree
114 River Lune LB composite bank profile, may be linked with groynes
115 River Lune RB composite bank profile, overgrazed, no trees
118 River Lune LB eroding bank
119 River Lune LB eroding bank
123 River Lune LB erosion, toe protection, willow stakes
124 River Lune LB erosion, protected with willow stakes
127 River Lune LB eroding bank
128 River Lune LB composite bank profile, overgrazed, no trees
129 River Lune LB eroding cliff and slumped material on toe, overgrazed, unfenced, no trees
130 River Lune LB eroding cliff and slumped material on toe, fallen tree, unfenced
131 River Lune RB eroding bank
132 River Lune LB composite bank profile
135 River Lune RB erosion, caused by fallen tree
136 River Lune RB eroding bank
137 River Lune RB eroding bank
140 River Lune RB eroding bank
141 River Lune RB eroding bank
144 River Lune RB eroding bank
149 Birk Beck RB eroding bank
151 Birk Beck LB ersosion from overgrazing
154 Birk Beck LB erosion from overgrazing
160 River Wenning LB erosion from overgrazing
164 River Wenning LB eroding bank
167 River Wenning RB erosion from overgrazing, gap in tree line
170 River Wenning LB eroding cliff, no trees, eroding embankment
174 River Wenning RB erosion, no trees
178 River Wenning RB erosing bank
180 River Wenning RB eroding bank
195 River Wenning RB eroding cliff overgrazed
200 River Wenning LB eroding bank
201 River Wenning LB eroding bank
206 River Wenning RB eroding cliff and slumped material on toe, attempted reinforcement with various materials
208 RiverWenning LB/RB eroding banks
218 Leck Beck LB eroding bank overgrazed
219 Leck Beck LB eroding cliff unfenced
220 Leck Beck RB eroding cliff unfenced
224 Leck Beck LB erosion exacerbated by upstream groyne and high flows on main river
229 River Lune LB composite bank profile, erosion exacerbated by groynes
230 River Lune RB erosing cliff
231 River Lune LB eroding cliff, unfenced
232 River Lune RB composite bank profile, unfenced
233 River Lune LB composite bank profile
278 River Lune RB eroding cliff
279 River Lune RB eroding cliff
300 River Lune LB poaching
301 River Lune LB poaching
302 River Lune RB composite bank profile, overgrazing
303 River Lune LB composite bank profile overgrazing/poaching
304 River Lune RB erosion associated with groyne

Figure 5.15 location of severe bank erosion

5.6.2 HISTORICAL ANALYSIS AND PLANFORM CHANGE

Historical evidence is useful in establishing stable and unstable reaches; such evidence also helps identify previous channel engineering. In conjunction with other sources it can show the extent and nature of past management and the timing and nature of morphological adjustment to such work.. Overall a historical perspective shows the persistence of a characteristic, whether there has been a trend or fluctuations over time and the rate at which changes have taken place (Hooke and Redmond, 1989). The accuracy of map derived data has been examined (e.g. Harley, 1975; Hooke and Kain, 1982; Downward, 1995); map scales of 1:2500 have a bank line accuracy of ±1 m (Hooke and Kain, 1982). Digitised data from modern 1:10000 maps read into a GIS, have bankline errors of 4 m which rises to 9 m for earlier 1:10560 maps (Downward, 1995).

A historical perspective was deemed appropriate to identify reaches of the River Lune, that are or have been, active in terms of lateral erosion and planform stability. For much of its length the Lune is confined by high river terraces, as a result the planform study was restricted to the main floodplain between Kirkby Lonsdale and the Crook of Lune below where the channel is once again confined. A smaller scale study was made of the short section of floodplain above Tebay. Several plans and maps exist for parts of the Lune at large scales (e.g. 1:2500) however it was felt that a scale of 1:10000 was appropriate for the aims of this study; data sources used are listed in Table 5.1.

Table 5.1 Historical Data

Map Date	Survey dates	Title	Source
1844	1844	O. S. County Series 1st Edition	Lancaster University Library
1890	1890/91	O. S. County Series re-survey	Lancaster University Library
1919	1910/1919	O. S. County Series 2nd Edition	Lancaster University Library
1957	1956/57/62	O. S. 1:10000 map	Lancaster University Library
1963	1963	Aerial Photograph	Lancashire County Council planning Dept.
1972	1972/76/77/83	O. S. 1:10000 map	Lancaster University Library
1988	1988	Aerial Photograph	Lancashire County Council planning Dept

The channel outlines for the main floodplain between Kirkby Lonsdale in the north and the Cook of Lune in the south are shown as individual traces in Figure 5.16. Notable channel changes are at the upstream end of the Caton meander (A) which was deliberately straightened in 1849 similarly the straightening of the Wenning (B) between 1919 and 1939 and the many changes upstream of Arkholme (C). The river above Arkholme has been a divided reach since at least the sixteenth century (Saxton, 1577) and has been the subject of a detailed study by Thompson (1984). Table 5.2 details the sinuosity changes for the reach shown in Figure 5.17 measured along the

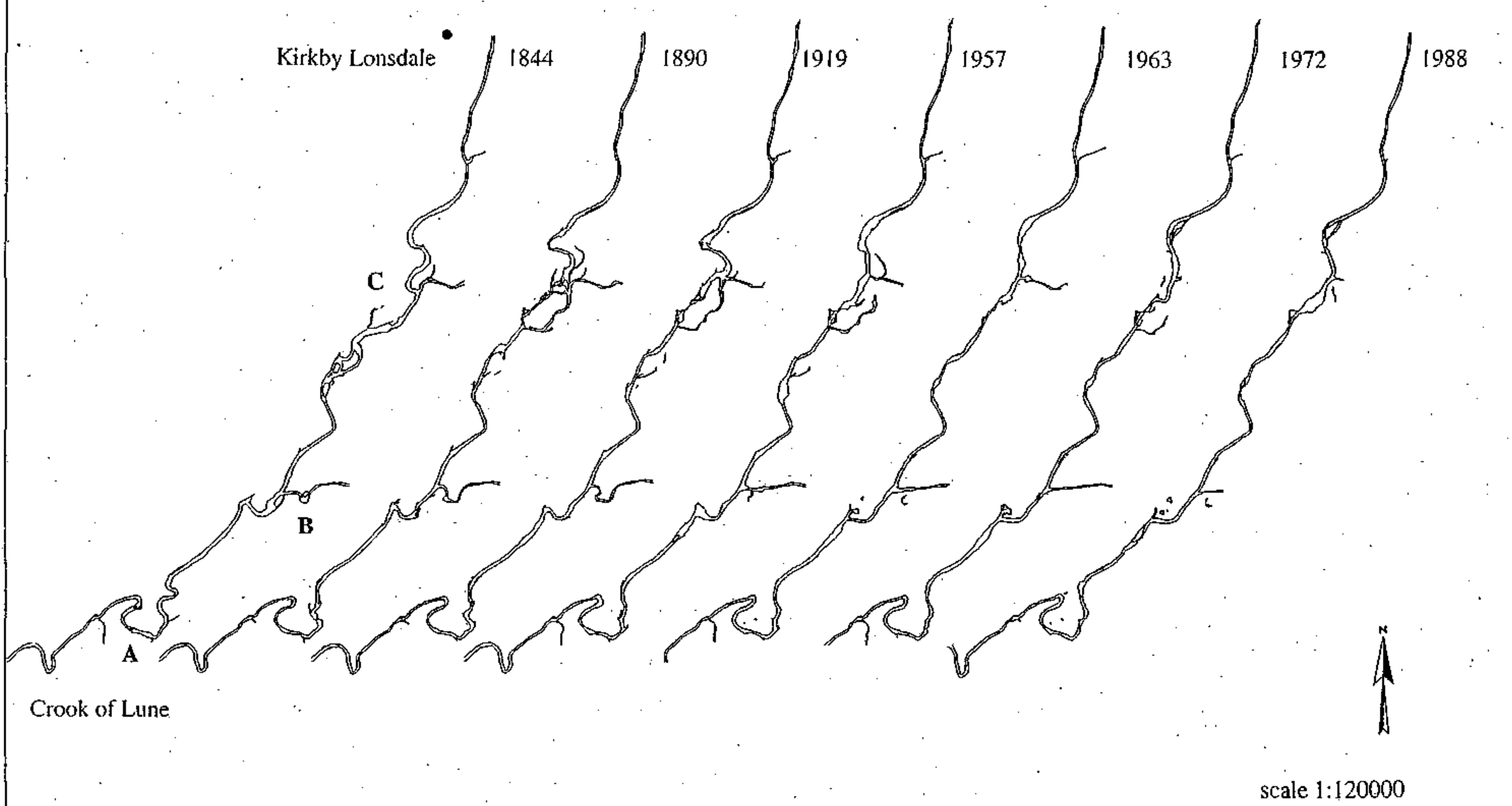


Figure 5.16 Channel changes on the main Lune floodplain

channel centreline, compared with the sinuosity changes observed by Thompson at the Arkholme reach.

Table 5.2 Sinuosity Changes

Date	**Sinuosity** Kirkby Lonsdale to Caton	**Sinuosity** Arkholme reach (after Thompson, 1984)
1844	1.33	1.38
1859		1.42
1874	1.33	
Unknown		1.65
1890		1.29
1910		1.27
1919	1.32	
1945		1.17
1951		1.08
1957	1.26	
1963	1.25	1.12
1969		1.15
1972	1.27	
1979		1.18
1981		1.14
1988	1.26	

It would appear that sinuosity has been progressively declining during the last century which is in large part due to engineering and revetment works. It should be noted that sinuosity does not reflect the total length of channel in a reach which, in this case has declined to a greater degree than sinuosity. The Arkholme reach declined from a maximum channel length in the late 19th century from 5.5 km to 3.75 km in 1981. Detailed analysis off the changes at site C are shown in Figure 5.17 where it can be seen that major channel activity occurs downstream of the confluence between the River Greta and the River Lune. The development of new channels between 1844 and 1894 may have been in response to the period of high rainfall in the 1890s, discussed in Section 2. Between 1919 and 1957 the eastern channel between the Greta and the Lune was largely abandoned except during floods, local rumour suggests that this change to the western channel was mechanically 'assisted'. Thompson (1984) attributed the degree of channel activity at this location to the nature of the bank material and the fact that Leck Beck and the River Greta join just upstream. The bank material is relatively incohesive as a result of historical channel activity whereby the banks are eroded in preference to incision in the floodplain. The two tributaries mentioned are steep and responsive catchments and may be contributing large amounts of coarse sediment. In addition the local slope of the channel at this location is low which may encourage deposition. Thompson (1984) calculated linear erosion rates for this area to be 3.66 m per year with maximum rates of 16.2 m per year between 1844 and 1979. The channel area has declined since 1844 from 4500 m to 3750 m in 1981 with a peak length of 5500 m between 1849 and 1890. He also observed that the rate of channel change was most closely associated with the stage of growth of meander bends rather than flood frequency.

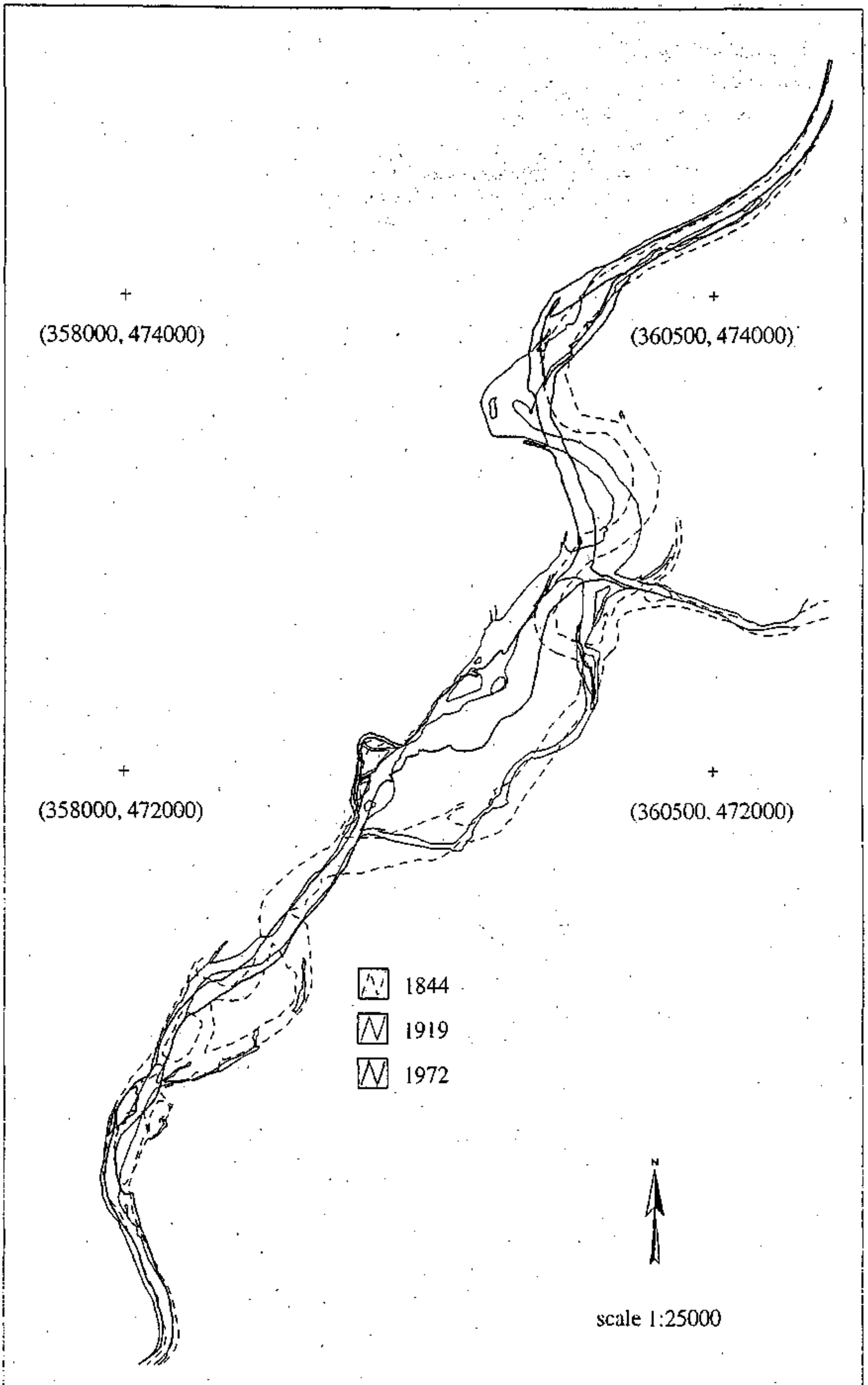
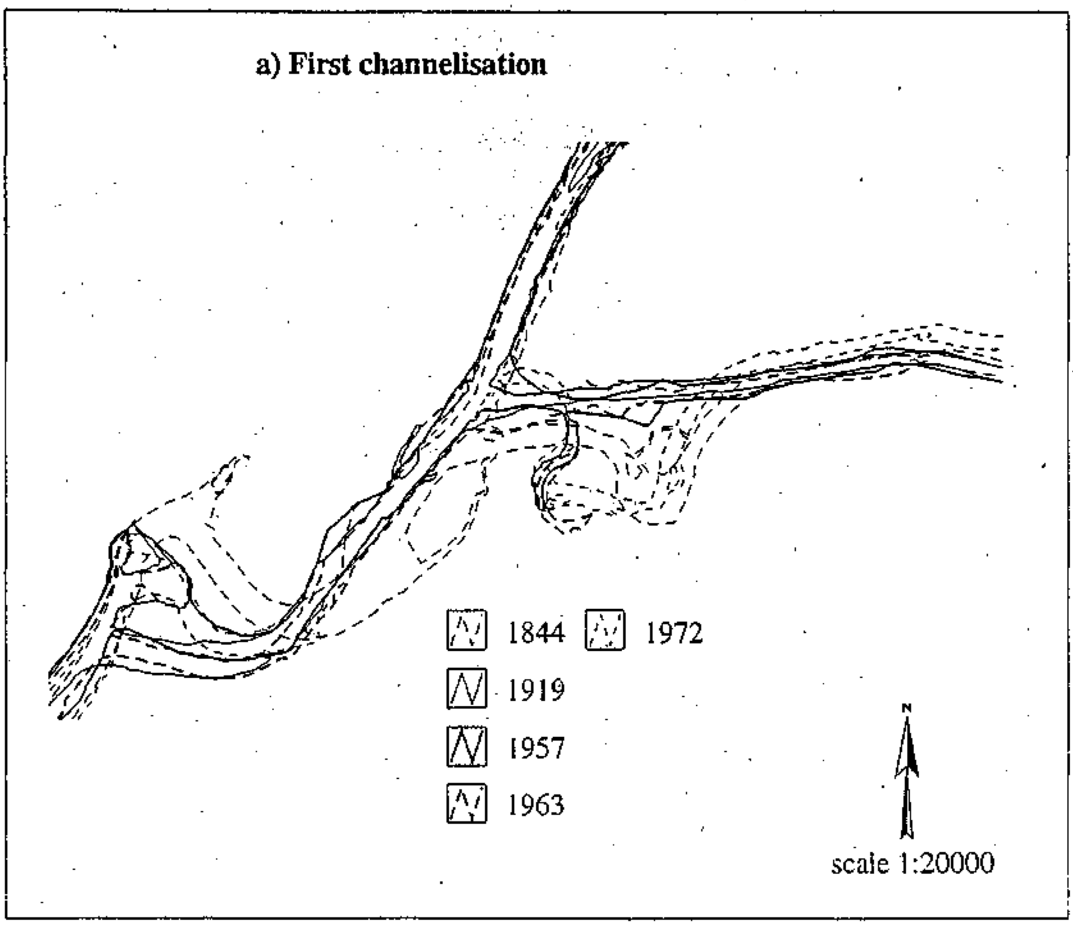


Figure 5.17 Channel Changes at Arkholme (C)

Detail of the channelisation on the Wenning (B) is shown in Figure 5.18a. After the original channelisation large sediment accumulations developed which were later the subject of a second realignment (Figure 5.18b). This site continues to have a sediment related problem with a large accumulation developing across the width of the channel and extending for approximately 150 m, effectively acting as an obstacle during high flows. The land owner regularly dredges this reach in an effort to prevent flooding onto his land. It is possible that this morphological problem was significant in the flooding of the nearby village of Hornby in January 1995. The Lune is a very dynamic and flashy river however the position of the channel has remained static over much of the floodplain during the last 150 years. The Caton meander bend (A), shown in Figure 5.19, has changed little with the exception of the straightened section mentioned previously. However recent field evidence and erosion suggests that the bend may be in danger of being cutoff at the neck. During a large flood in late October 1998 large areas of the floodplain were inundated, the flood water was observed to have formed a distinct and fast flowing channel across the neck of the bend. If this bend does cutoff considerable channel changes may be expected at other locations as the river attempts to adjust to its reduced length and increased slope.

The planform of the upper Lune floodplain from the Lune gorge at Tebay upstream to Newbiggin is shown in Figure 5.20. The extensive channelised reach and the downstream meander bend together with some changes above Tebay at the junction with the M6 motorway are the only major channel changes in this reach. However there is considerable channelisation in the very upstream reach where channels have become drainage ditches.



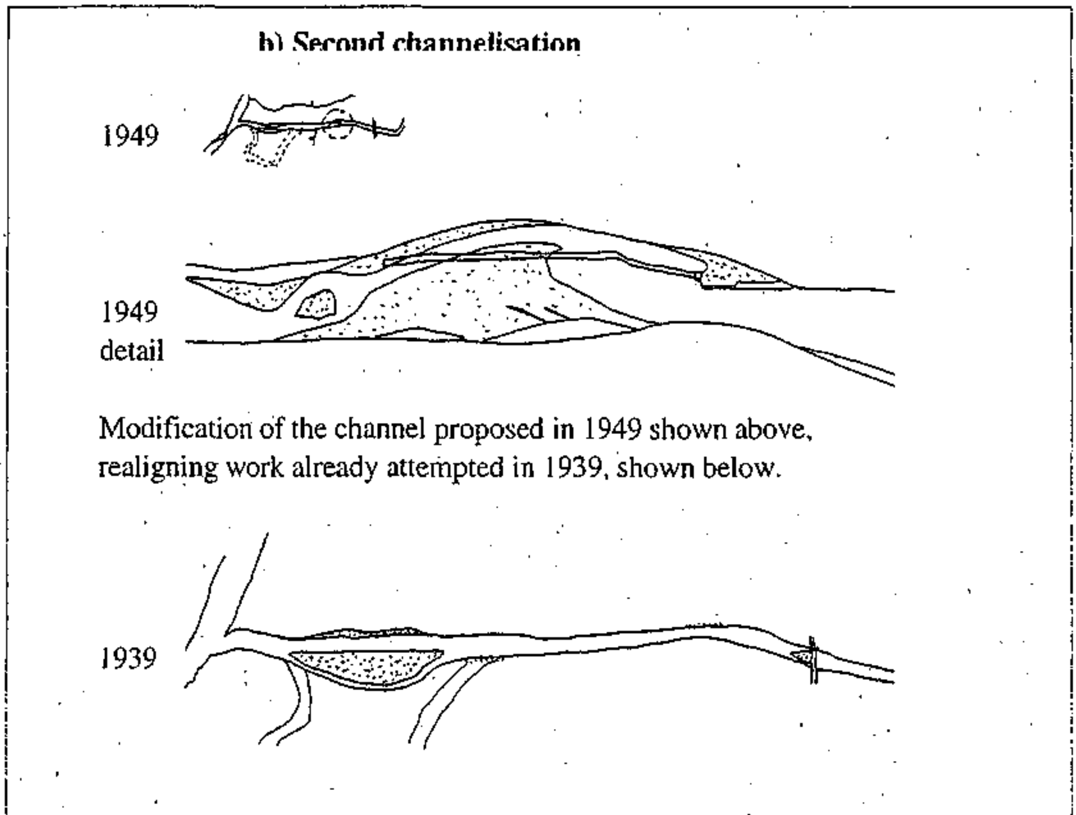


Figure 5.18 Channel Changes on the Wenning (B)

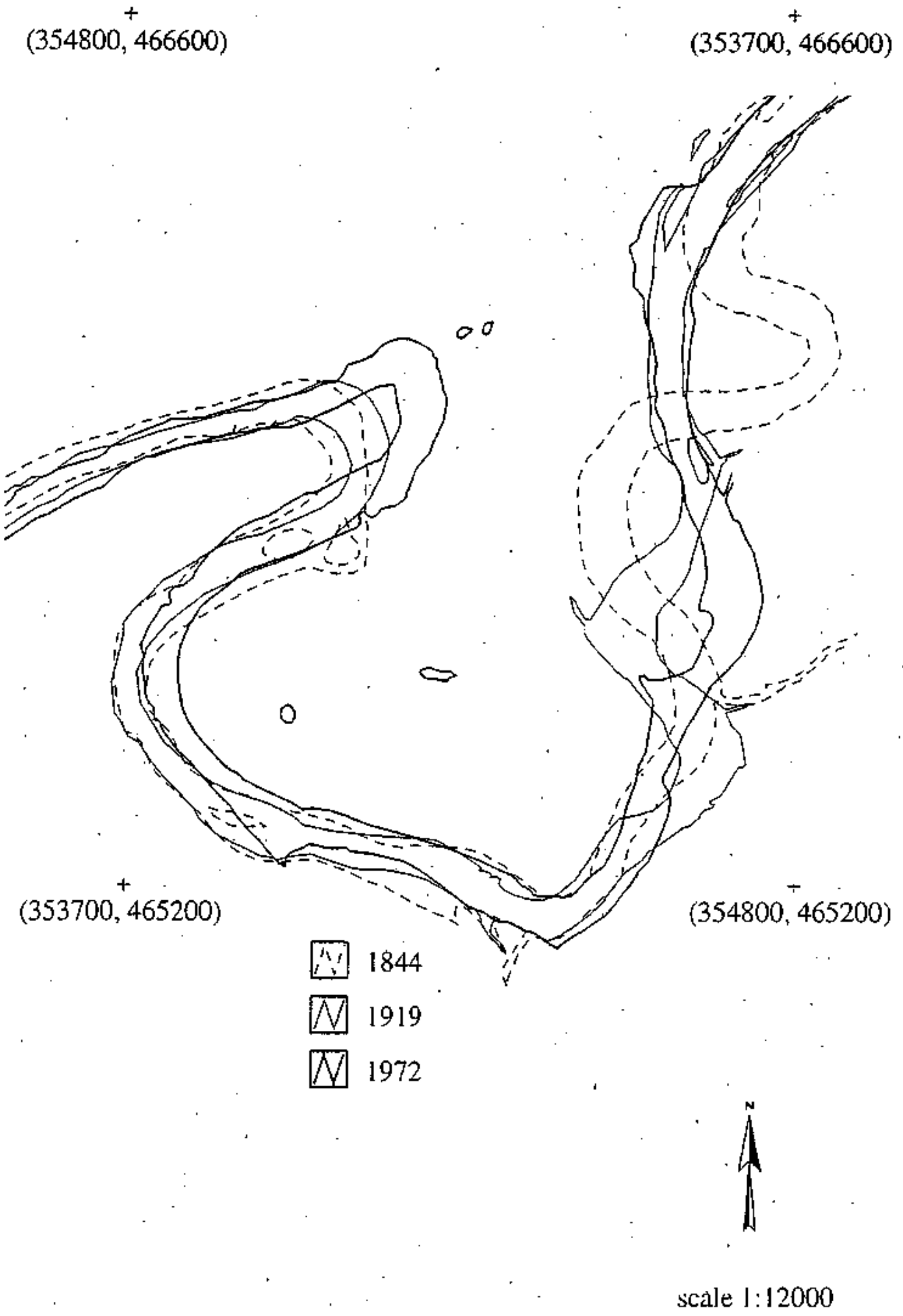


Figure 5.19 Channel Changes at Caton (A)

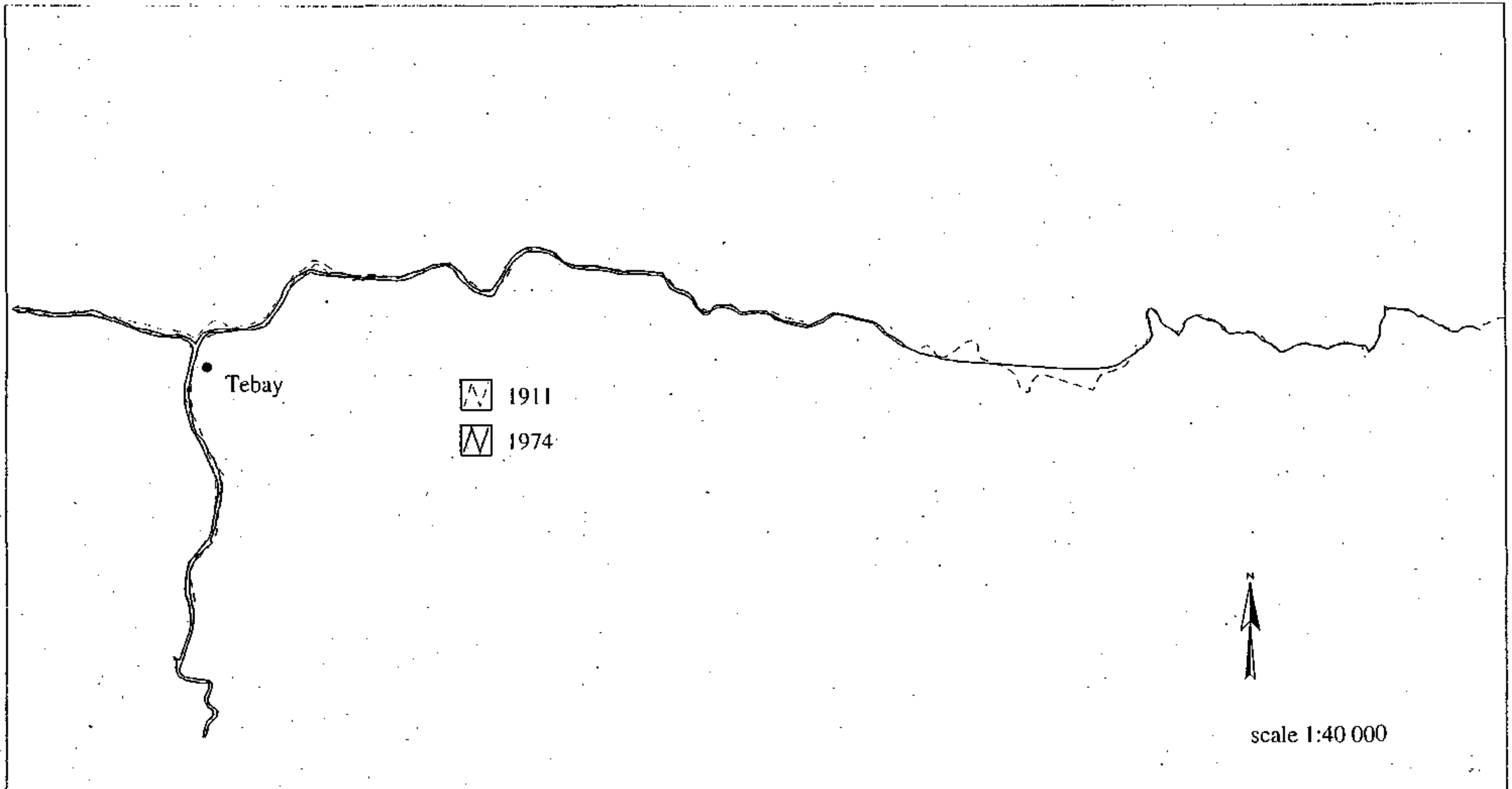
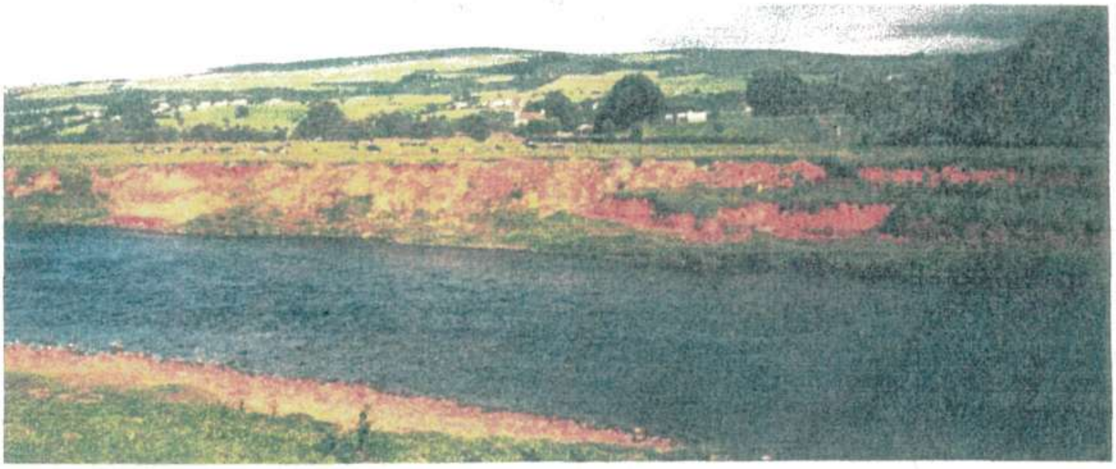


Figure 5.20 Channel Changes at Tebay

5.6.3 CHANNEL TYPOLOGIES

The main river of the Lune has been divided into 10 reaches that share a common typology. The following figures (5.21 to 5.31) describe each reach in terms of physical characteristics and some comments are made regarding the condition, likely changes and recommendations for future management. The typologies are useful in obtaining a general picture of the state of the river and may be used as tools by Environment Agency staff in attempting to assess the suitability of applications for land drainage consent and also to target river restoration efforts to key areas.

Relevant information is given for calculating for example, riffle or bar spacing using the equations presented earlier in this section. Riffle spacing can be calculated from theory and compared with field observations to give a rough idea of the state of the current bed topography. Any future restoration or habitat improvement work should consider appropriate bed topography for individual reaches. Detailed measurements of channel cross section and not currently available ands should be measured in the field. A long-term monitoring program has been initiated to examined changes in channel geometry especially width and depth for the future. Initial survey information will be available from Flood Defence in 1999.



Loyn Bridge to Crook of Lune (GR. 360000, 474100 to 358200, 469500)

River length = 10.754 km Channel slope = 0.0009   Valley slope = 0.0013

Bed material predominantly gravel and pebble size, banks predominantly earth with extensively steep banks with composite, undercut and vertical and toe profiles. A variety of resectioned, reinforced, embanked and poached banks. The banks are largely unfenced and badly eroding, isolated trees on the left bank and occasional clumps on the right bank but no overhanging branches or exposed roots. The flow type is extensively glide with some boils and marginal deadwater.

Features:

Pools,	5
Riffles,	15
Point bars	4
Vegetated point bars	2
Side bars	14
Vegetated side bars	2
Mid channel bars 5	
Vegetated mid bar	1
Mature island	3
Weirs,	1
Groynes 17	
Road bridges	2

Comments:

Severely eroding banks throughout most of the reach, little variety in bed morphology, would benefit from extensive stock exclusion from river banks which should reduce channel width and increase low flow water depths. Degraded reach, banks prone to severe erosion during floods, poor habitat.

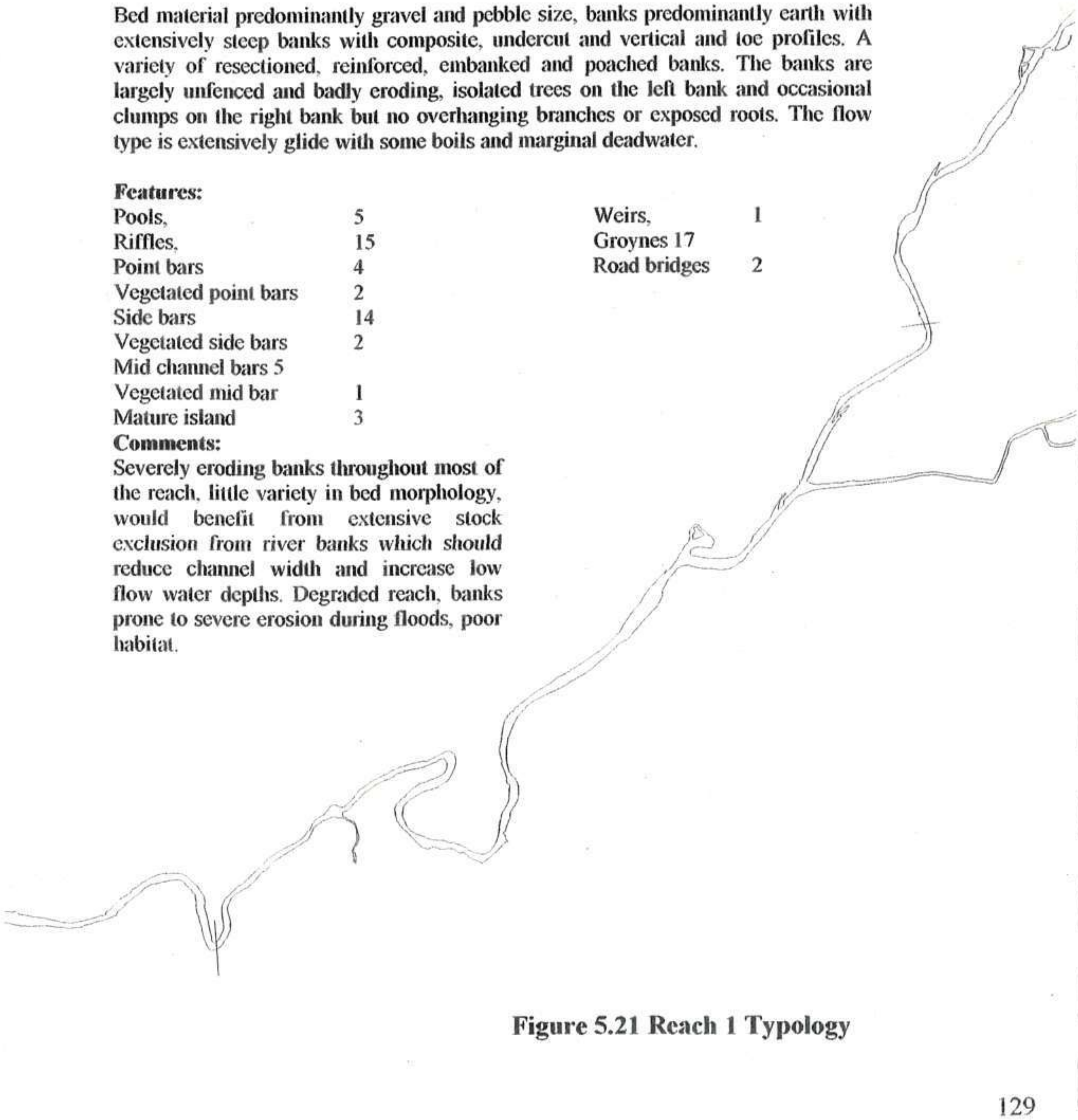
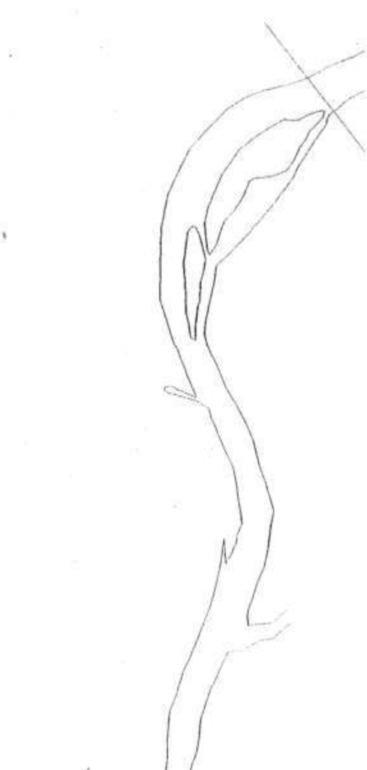


Figure 5.21 Reach 1 Typology



Newton to Loyn Bridge (GR. 361600, 478100 to 360000, 474100)

River length = 5.607 km Channel slope = 0.0018 Valley slope = 0.002

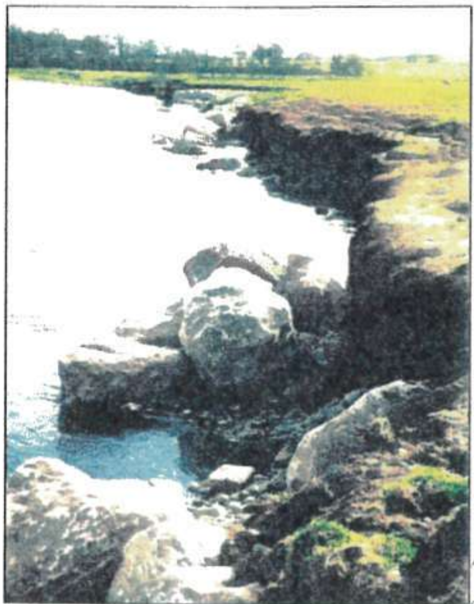
Bed material predominantly gravel, pebble and cobble, bank material earth with some river gravels. Bank profiles are predominantly gentle but also steep and composite are present. Isolated trees on the left bank and occasional clumps on the right. Heavily reinforced banks, remnants of set back embankments and poaching on banks. Flow type, extensively glide with some up-welling boils and marginal deadwater.

Features:

Pools,	1	Groynes,	3
Riffles,	9		
Point bars,	1		
Vegetated point bars,	1		
Side bars,	11		
Mid channel bars	4		
Mature islands,	2		
Attached ox-bow wetlands,	2		

Comments:

Historically the most active reach on the Lune with high rates of lateral channel migration and bank erosion from fluvial activity, rapid channel changes should be anticipated.



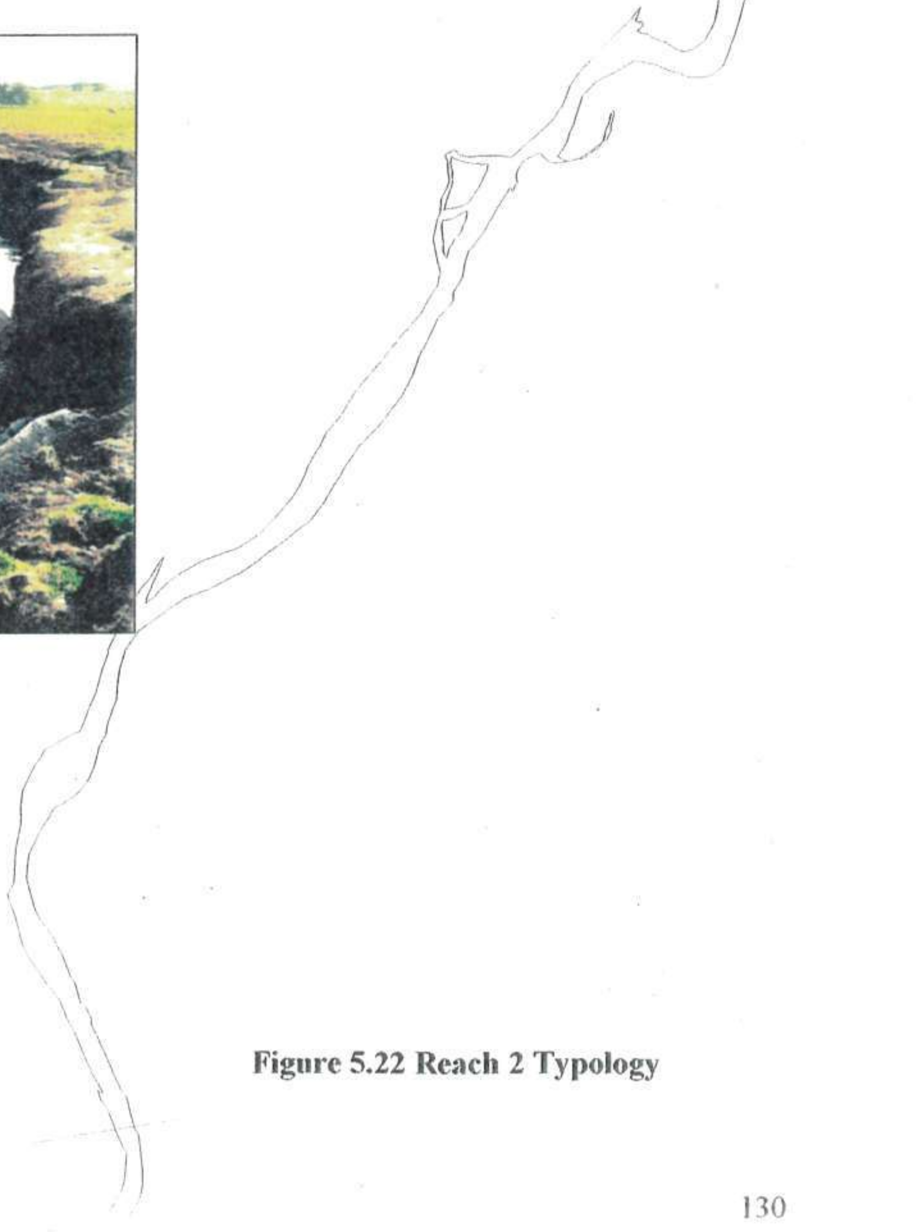


Figure 5.22 Reach 2 Typology

Devils Bridge to Newton (GR. 361700, 484900 to 361600, 478100)

River length = 4.69 km   Channel slope = 0.0021   Valley slope = 0.0023

Bed material predominantly gravel/pebble, some emergent bedrock and cobbles, bank profiles are extensively steep, with vertical/ undercut and composite with poached banks in places. Occasional clumps of trees, mostly unfenced banks. Flow types are extensively run and glide, river terraces confine the upper section.

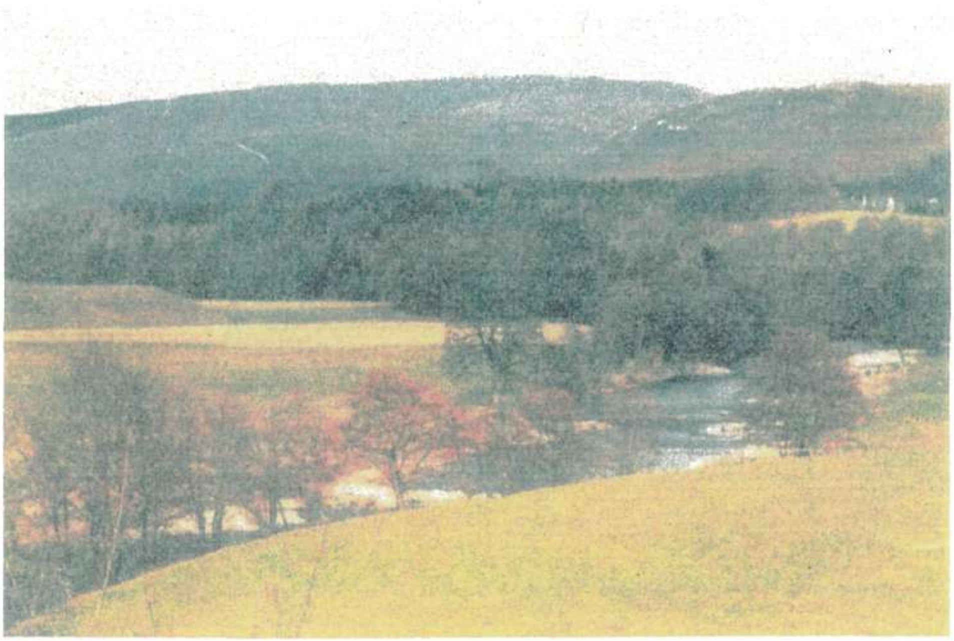
Features:

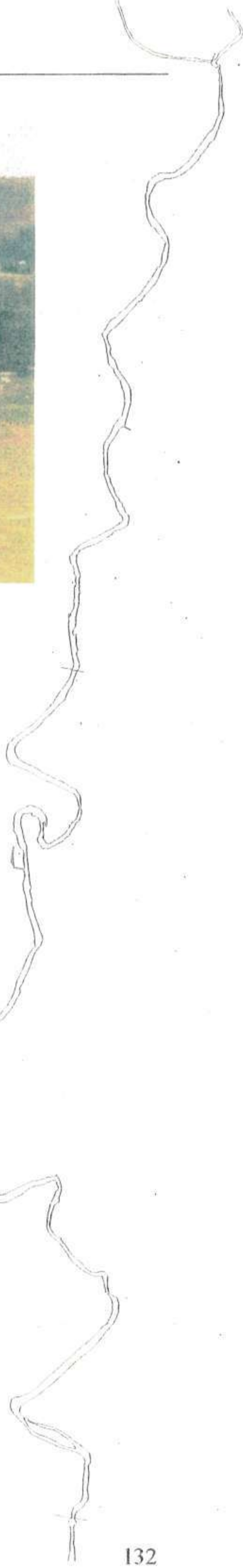
Pools,	2	Groynes,	10
Riffles,	9		
Point bar	1		
Vegetated point bar,	1		
Side bars,	11		
Mid channel bars,	1		

Comments:

Clear evidence of channel widening with badly damaged banks, where stock fencing is functioning, banks are apparently more stable.

Figure 5.23 Reach 3 Typology





Rawthey confluence to Devils Bridge (GR 362800, 489600 to 361600, 478100)

River length = 15.58 km   Channel slope = 0.0026   Valley slope = 0.003

Substrate cobble and gravel/pebble with some emergent bedrock and boulders, earth banks with extensively steep and gentle profiles, limited amount of composite banks and poaching. Flow types are run and glide with some marginal deadwater. Trees are semi-continuous and the river is confined in a narrow floodplain with river terraces.

Features:

Pools,	12	Groynes,	25
Riffles,	33	Road bridges,	2
Point bars,	14		
Vegetated point bars,	6		
Side bars,	30		
Mid channel bars,	10		
Vegetated mid bars,	4		
Mature islands,	2		
Eroding bluffs,	2		

Comments:
The channel in this reach meanders across a narrow flood plain although river terraces restrict lateral movement. The bed morphology is diverse and represents a generally good physical habitat, compared with lower reaches. There are limited cases of severe erosion with the exception of erosion linked with the large number of groynes.

Figure 5.24 Reach 4 Typology

The Lune Gorge
Lowgill viaduct to Goodies Farm (GR 361100, 503100 to 362400, 496900)

River length = 3.57 km   Channel slope = 0.003 Valley slope = 0.003

Substrate is cobble and bedrock with mostly steep and some gentle bank profiles, bank material is extensively earth and some bedrock. The channel is confined by river terraces and has step-pool morphology. Trees are semi-continuous, flow types include cascades, rapids, glides and marginal deadwater.

Features:

Pools,	7
Riffles,	2
Point bars,	2
Side bars,	9
Mid channel bars,	2
Mature islands,	6

Goodies farm to Rawthey Tributary (GR 362400, 496900 to 362800, 4194500)

River length = 5.77 km   Channel slope = 0.007   Valley slope = 0.007

Substrate is bedrock between Goodies farm and the viaduct where banks are also bedrock, the flow is step pool with cascades and no riffles (approx. 1.5 km). Below the viaduct the valley is wider with some riffles and bedrock and cobble substrate. Bank profiles are extensively steep or gentle, limited composite banks and poaching. The flow is very diverse with cascades, rapids, a small waterfall, glides and some marginal deadwater. Throughout the whole reach trees are semi-continuous.

Features:

Pools,	9	weirs,	2
Riffles,	3		
Point bars,	6		
Side bars,	20		
Vegetated side bars,	5		
Mid channel bars,	4		
Mature islands,	2		

Comments:
This reach is an extension of the Lune gorge and is stable due to the extensive bedrock and confining river terraces. Bank erosion is limited to a few isolated locations. The habitat is varied and of high value.

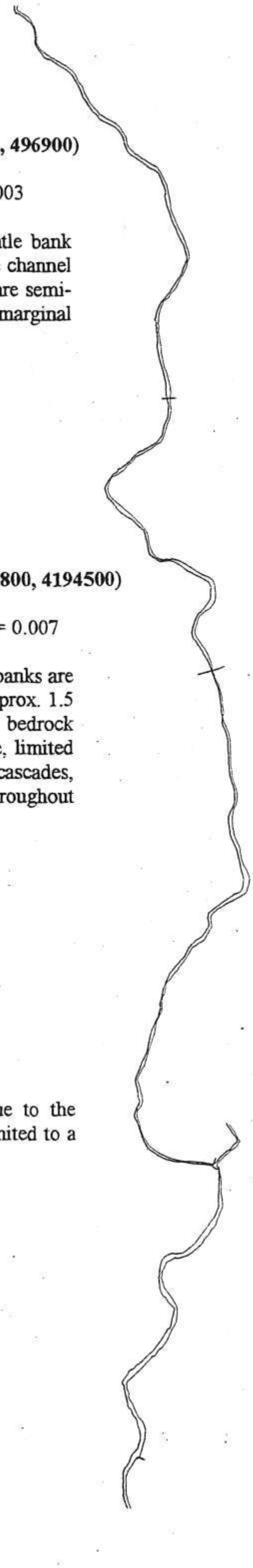
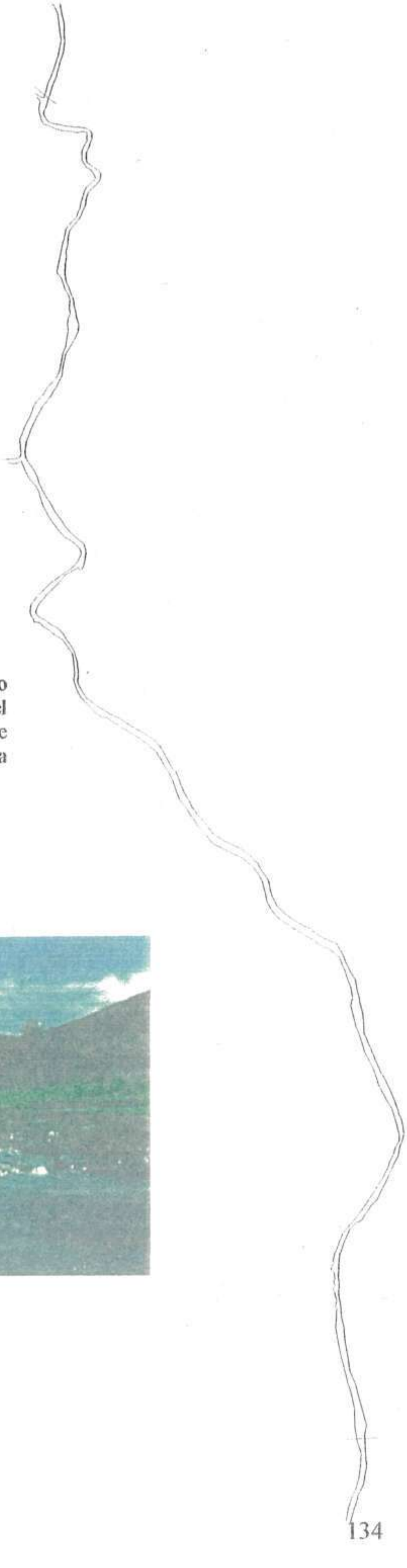


Figure 5.25 Reach 5 typology



Roundthwaite to Lowgill viaduct (GR 361200, 505200 to 361100, 503100)

River length = 7.36 km   Channel slope = 0.005
Valley slope = 0.006

Substrate is cobble and bedrock (boulders) with mostly steep and some gentle bank profiles, bank material is extensively earth and some bedrock. The channel is confined by steep river terraces and has step-pool morphology. Trees are semi-continuous, flow types include cascades, rapids, glides and marginal deadwater.

Features:

Pools,	7	Weir,	1
Riffles,	5		
Point bars,	7		
Side bars,	18		
Vegetated side bars,	2		
Mid channel bars,	2		
Mature islands,	1		
Eroding bluffs,	1		

Comments:
Stable and steep reach, the entrance to the Lune gorge, no major erosion problems although there are large gravel bars at some locations where culverts draining under the M6 motorway join the main river. Sediment build up as a result is a potential problem.

Figure 5.26 Reach 6 typology

Raisgill Hall Bridge to Roundthwaite (GR 364500, 505500 to 361200, 505200)

River length = 4.89 km   Channel slope = 0.008   Valley slope = 0.018

Substrate is gravel/pebble and cobble, banks are earth and extensively steep with some vertical/undercut and gentle banks. There are isolated clumps of trees, the flow type is run and glide. Unfenced banks are eroding.

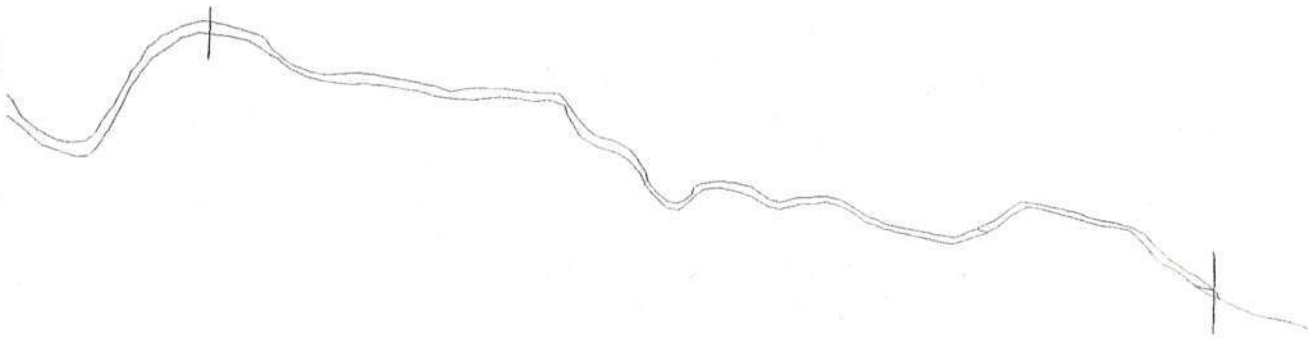
Features:

Pools,	2	weirs,	3
Riffles,	17		
Point bars,	4		
Side bars,	extensive		
Vegetated mid bars,	1		

Some boulders, largely derived from failed revetments and deliberate introduction

Comments:
The upper reach above Tebay is showing some sign of instability as a result of the extensive channelisation work upstream. The large upstream meander is proving difficult to protect from lateral erosion, the solution may be to allow extension of this bend to provide additional depositional areas to replace those lost upstream. Grazed and bare banks are particularly likely to erode in this reach. Habitat value in this reach is generally poor.

Figure 5.27 Reach 7 Typology



Kelleth to Rayne Bridge (GR. 367400, 505100 to 365800, 505200)

River Length = 2.75 km   Channel slope = 0.004   Valley slope = 0.004

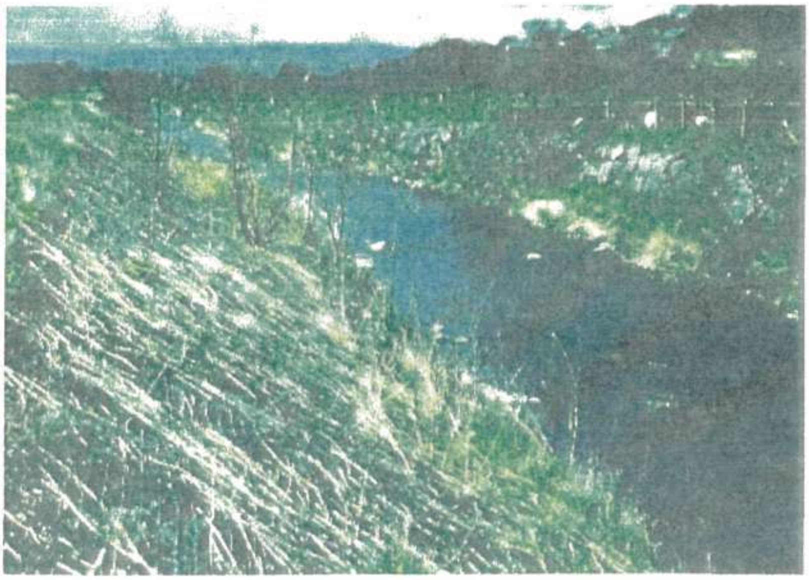
Substrate is predominantly gravel/pebble and cobble; bank profiles are steep and vertical there are occasional clumps of trees. The flow type is run and glide and riffle. There are some resectioned and reinforced banks; banks are very stable where woodland adjoins.

Features:	
Pools,	1
Riffles,	28
Point bars,	3
Mid channel bars	1

Comments:

Relatively stable reach with woodland on right bank and fenced left bank, some tipping on the left bank.

Figure 5.28 Reach 8 Typology



Waterfall to Kelleth (GR. 368450, 505150 to 367400, 505100)

River length = 1.52 km   Channel slope = 0.007 Valley slope = 0.001

Cobble/gravel substrate, no trees, fenced along entire length. Realigned channel 100% resectioned reinforced banks, revetments in various states of collapse, fallen blocks creating some flow diversity. The channel has formed a regular riffle spacing to attempt to reduce channel slope but there is no opportunity for meander development. Flow type riffle/run.

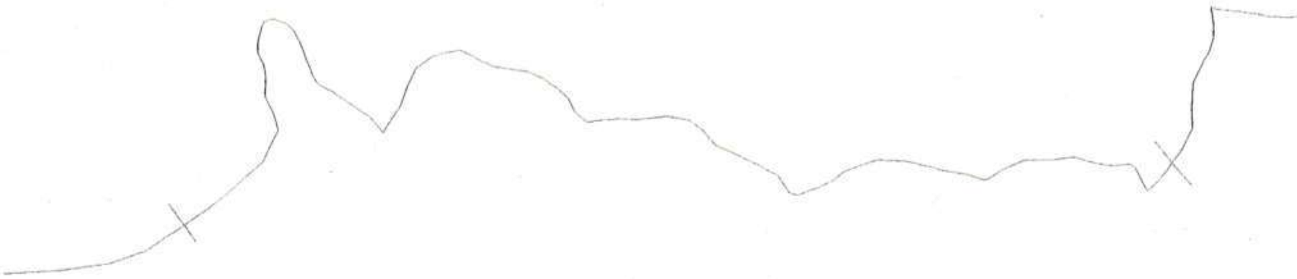
Features:

Pool	1
Riffles	11

Comments:

This reach is in a severely degraded state and will not recover unassisted, instability has been transferred to sites both up and downstream but also remains within the channel, hence continued erosion of the banks. Improvement of this reach for habitat and to reduce resulting instability elsewhere requires the sinuosity to be increased. Most obvious solution would be to return the channel to its previous position at considerable cost, such a scheme would involve the construction of two road bridges; funding opportunities should be explored. The benefits of such a scheme would however be considerable. Less costly options would be to move the current channel to the terrace end on the extreme right of the floodplain with considerable inconvenience and loss of land to the landowner.

Figure 5.29 Reach 9 Typology



Wath to Waterfall (GR. 369300, 505350 to 368450, 505150)

River length = 2.17 km   Channel slope = 0.01   Valley slope = 0.01

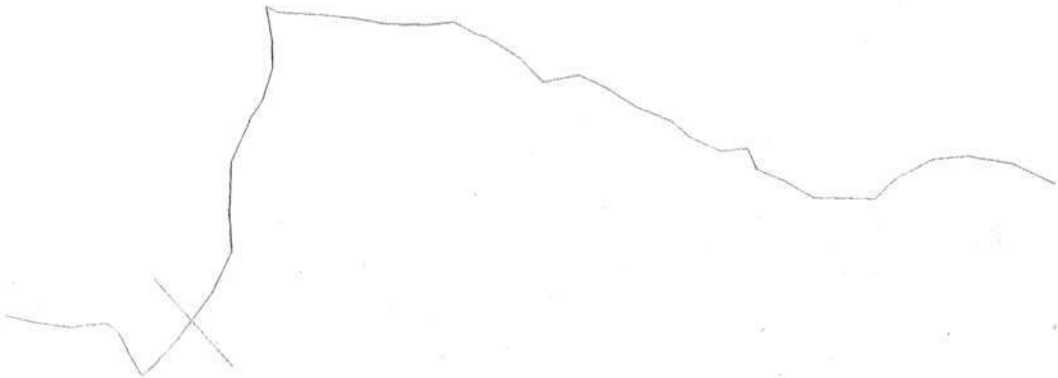
Cobble substrate, with a variety of bank profiles, steep, gentle, vertical and undercut. Flow type is varied extensively runs but with marginal deadwater, bedrock and occasional large cobbles, trees are isolated and there is notable bank erosion in the lower part of the reach particularly

Features:

Pools	4	Eroding bluffs	2
Riffles	22		
Point bars	1		
Side bars	extensive		
Mid channel bars	3		

Comments:
This reach has potentially good habitat quality with varied bed forms and flow types. However the effects of the engineered reach immediately downstream are evident in recent, and in places severe erosion.

Figure 5.30 Reach 10 Typology



Newbiggin to Wath (GR. 369300, 505350 to 370200, 505300)

River length = 0.97 km Channel slope = 0.01 Valley slope = 0.01

Gravel pebble substrate, largely resectioned reach with smooth and ponded flow in places some runs, glides, riffles and pools. Some evidence of channel recovery in places shown by the existence of berms. No trees but other waterside plants e.g. iris, and extensive ranunculus.

Comments and recommendations:
This reach is an overdeep drainage channel with little variety of bed form or flow type, improvements could be made by producing a two stage channel within the existing high banks, as there is some sinuosity of planform, this could be extended within a two stage channel.

Figure 5.31 Reach 11 Typology

5.7 DISCUSSION

The main river of the Lune in the two floodplain areas (i.e. above Tebay and below Kirkby Lonsdale) is showing signs of instability, in the form of bank erosion which in the lower reaches is severe and extensive. The cause in many locations appears to be resulting from local overgrazing leading to shallower and wider channels and composite bank profiles. However the importance of increased stream power from land use changes and recent climatic variability should also be considered. Both factors operate simultaneously such that increased rainfall intensity leads to more frequent flooding, the response of the flood wave is more rapid as a result of land drainage activity and possibly through the impacts of grazing in upland areas. The resultant floods have a relatively greater impact on rates of bank erosion and channel change due to the high proportion of bare and easily eroded bank material. Sources of sediment for contemporary channels are usually derived from the channel margins.

The changes described have lead to much of the channel of the Lune being in a degraded state both geomorphologically unstable and providing poor physical habitat. In many locations localised widening and shallow flows are obvious, data are insufficient to determine whether widths and depths have significantly changed in the recent past. However evidence in the literature suggests that this is very likely given the historical use of the Lune catchment and the extent of engineering work and channel modifications. The most stable reaches which have the greatest flow diversity and a range of water depths are those that are bordered by consolidated banks (some with bedrock and high terraces) and those protected by tree roots. In nearly all locations where stock have direct access to the river, bank erosion is severe and bank collapse and localised widening are obvious.

It is probably that some geomorphic adjustment to the changed flood frequencies over the last 50 years would have occurred. This process will have added to the instability problems described above. However there has been no major change in very large floods suggesting that the channel is not attempting to accommodate larger discharges although the effects of major floods (e.g. January 1995) on channel change are hard to quantify. The channel is designed naturally to accommodate the whole range of flows; the range does not seem to have changed only the frequency of some events whose major impact is to accelerate bank erosion. The evidence from field observations, map work and hydrological analysis suggest that the impacts of human activity within the catchment and on the river bank are largely responsible for the degraded state of much of the main river of the Lune.

If climate continues to be more variable with drier summers and wetter winters the environmentally insensitive land and river management of the Lune catchment will lead to further degradation, instability, erosion and siltation problems. A stable fluvial geomorphology will clearly withstand the effects of future climate variability more readily than a degraded and eroding system. Recommendations towards achieving a robust and sustainable river system are made in Section 6.

5.8 SUMMARY

Land drainage activities have produced instability problems in the Lune that the river has been unable to adjust to, despite the instability being moved both up and downstream. Direct channel modifications have resulted in a loss of deposition features; new deposition areas have developed in response that may be giving the impression of increased gravel deposition.

Sediment related problems account for much of the flood defence maintenance and new works activity. Incorrect or, non identification of the cause of sediment deposition has resulted in failed works that have been destroyed by floods or have merely shifted a problem to another location. A majority of bank revetments on the main channel of the Lune have been followed by erosion up or downstream.

Severe erosion of river banks on the Lune in its main floodplain extends to 40% (includes revetments and sites of severe erosion); more moderate erosion is evident along much of the remaining banks. Physical habitat in this area is poor and instability is likely to continue unless good vegetation cover protects bare banks. However the cause of erosion problems is not simply related to stock access and overgrazing of river banks.

Field and moor drainage combined with intensive grazing of upland vegetation and intense winter rainfall over the last 25 years have jointly contributed to a change in the flow regime of the River Lune. This threshold change is continuing and a state of dynamic equilibrium has not been reached. Stream power has been increased (by more frequent floods) sufficient to accelerate erosion of banks left vulnerable by grazing animals.

SECTION 6 IMPLICATIONS FOR RIVER AND CATCHMENT MANAGEMENT

6.0 INTRODUCTION AND OBJECTIVES

It is the intention of this section to discuss the implications of the preceding sections for river management and to make recommendations for management of the river Lune based on the findings of this study. The recommendations, together with the background information from the catchment, constitute a major step towards truly integrated catchment management by providing essential physical information about the catchment. The approach used and recommendations made, take full account of the uncertainty of future climate; water demand and flood risk and maximise the opportunities for sustainable development.

For hundreds of years engineers have provided benefits to society in the form of flood protection, water supplies, navigation and power generation. With time, engineering feats have grown from reach scale works to major inter-basin transfers, large reservoirs and river realignments. Increasingly large areas of land have been made available for agriculture through land drainage activities. Undoubtedly the engineering community has provided major health benefits through potable water supplies and protection from flooding. The contribution of river engineering to the economy is equally large. Engineers have historically responded to the demands of society and provided the required solutions. In recent decades the demands of society have changed dramatically.

Predicted scenarios of climate change are likely to place increasing pressure on water supplies in an atmosphere of ever-increasing demand from industry, agriculture and for domestic use combined with greater risk of flooding. Environmental awareness has grown sufficiently over the last thirty years to become part of mainstream culture. Society now demands that in addition to exploitation of water resources for traditional uses, water bodies and rivers must now be fit for recreational use and be able to support a range of diverse habitats and an abundant ecology. We expect our rivers to have conservation value.

Institutional change has reflected society's expectations with the development of the National Rivers Authority and subsequently the Environment Agency with aims to promote sustainable development. Both these organisations have incorporated the disciplines of pollution control, water resources, ecology and fisheries. The more traditional roles of the water authorities, particularly flood defence still maintain the duty to protect but have undergone considerable change in becoming more environmentally sensitive. The ongoing adjustment process has often been difficult and practitioners operating from different standpoints often have no common reference or language. In practice problems often arise between engineers who are attempting to modify the physical environment and ecologists who are attempting to protect the flora and fauna living in these systems. The common ground is the lack of understanding of sediment and discharge regimes and hence the behaviour of river systems. Rivers always respond to changes in discharge and sediment, these changes may be observed in the resulting instability which may be caused by catchment wide land use and or reach scale realignment. The nature, spatial extent and timing of erosion are the domain of fluvial geomorphology. The application of fluvial geomorphology to river engineering and habitat management is vital to attain truly integrated catchment management.

Catchment management as a principle relates to all the activities operating within a catchment in the case of the Lune these are largely: farming practices, water abstractions and fishing activity. The Environment Agency has a policing role and acts on best practice and best available information. This study provides background information on the physical and climatic process operating within the catchment. Recommendations are presented to the agency for future management of the catchment both in terms of implementing catchment planning and for short-term flood defence activities. Recommendations take account of Agency policies across all its functions.

6.1 REVIEW OF ENVIRONMENT AGENCY POLICY AND BEST PRACTICE

6.1.1 Legal framework for flood defence

The principle legislation relating to flood defence includes the Water Resources Act 1991(WRA 1991), the Land Drainage Acts 1991(LDA 1991) and 1994 (LDA 1994) and the Environment Act 1995 together with any local bylaws. Under the WRA 1991 and LDA 1991, the Agency has a duty to exercise a general supervision over all matters relating to flood defence. The Agency must carry out surveys of the areas in relation to which it carries out flood defence functions and input data to strategic plans. The Agency may also construct new works and undertake improvement and maintenance works on, or in connection with main rivers. However the Environment Act 1995 requires that the Agency undertake its duties within a framework of sustainable development.

It is not the intention here to list all the legislation relating to flood defence, but rather to address policy and best practice requirements relating to the Environment Act 1995. For the purpose of this study the obligations and duties for flood defence are divided into two sections; those concerned with determining long-term requirements for flood defence and those relating to maintenance operations. The statutory requirements and policy recommendations are applicable to all flood defence operations, however it should be noted that particular emphasis is placed, in this report, on policies applicable to large, rural catchments with largely undeveloped floodplains, specifically the River Lune.

Assessing long-term flood defence requirements

It was sometimes suggested that the NRA could have been more pro-active in the discharge of its general supervision duties (Institute of Civil Engineers, 1996). The general supervision requirement imposed on flood defence functions is most appropriately combined with the need to take a catchment scale view (NRA, 1993) and the achievement of sustainable development (Environment Act, 1995). Section 4 of the Environment Act 1995 requires that ministers give statutory guidance to the Environment Agency on objectives that they think it appropriate for the Agency to pursue. The first such guidance was issued in November 1996, specific strategic objectives set by Government are given in 'The Environment Agency and sustainable development' (1996), specific objectives require the Agency to develop detailed objectives and targets. The explanatory notes accompanying this statutory guidance document give specific advice to individual functions. However stress is placed on the importance of interplay between the different functions in order to ensure that the potential impact of the Agency's actions are addressed for the environment as a whole. The guidance for flood defence is listed below:

> "The aim of government policy on flood...defence, which is consistent with sustainable development, is to reduce the risks to people and to the developed and natural environment from flooding and coastal erosion. The safeguarding of life is clearly of the highest priority, but environmental and economic factors should be integral to decision making and opportunities should be taken as appropriate to enhance the environment. Policy starts from the presumption that except where life or important natural or man-made assets are at risk, natural river or coastal processes should not be disrupted. The effects on wildlife habitats are a key consideration. Defence measures should be part of a strategic plan for the ... river catchment concerned. In addition, defence measures must be shown to be in the national interest in economic terms, taking account of all likely costs and benefits, including environmental ones."

The Environment Agency have produced some introductory guidance on its contribution to sustainable development, the policy for flood defence is listed below:

> "Sustainable flood ... defence schemes are defined as those which take account of natural processes and of other defences and developments within a river catchment ... and which avoid as far as possible committing future generations to inappropriate options for defence. The Agency will be expected to act in accordance with this policy. In addition, it will be expected to discourage inappropriate development in areas at risk from flooding."

The supervisory role imposed on the Agency flood defence function requires that strategic plans be made for river catchments. The NRA Flood Defence Strategy (1993) states that the improvement of defences should be conducted by catchment, working towards a better understanding of natural processes to ensure improvements work with nature and promote the use of soft engineering where appropriate. In addition, with respect to climate change, the Agency (then NRA) will ensure that its assets are developed in the best possible way to meet future demand. Flood defence, together with all the Agency functions, has a duty to work with all sectors of society and to exercise its functions in combination as stated in the 'Introductory Guidance on the Agency's contribution to Sustainable Development' (undated). It is recognised in this document that to achieve a holistic approach, working with all aspects of society is an area that requires further development within the Agency. In addition use should be made of integrated catchment management planning or other integrated geographic planning tools.

Some legislation exists with respect to supervisory responsibilities; S.107(2) WRA 1991 and S.21 LDA 1991 enable the Agency and Internal Drainage Boards to enforce certain obligations to which landholders are subject by reason of tenure, custom and prescription (Institute of Civil Engineers, 1996). However these enabling measures relate principally to enforcing landholder responsibilities towards ensuring the proper flow of water or to the maintenance of certain structures for which the landholder is responsible. Under S.66 LDA 1991, the Agency may also make bylaws relating to main rivers. These generally concern the erection of fences, disposal of rubbish, excavation affecting the beds or banks of rivers, erection of jetties and walls, tree planting, use of vehicles on river banks, damage caused by fishing, grazing, consenting arrangements and similar matters (Institute of Civil Engineers, 1996).

The most useful legislation through which the Agency can enforce its supervisory duties is the Land Drainage Consent procedure. The Agency has an overriding duty to improve the aquatic environment for conservation reasons, when considering proposals relating to its functions. These duties of the Agency and IDBs also apply to others when consent is given to carry out work under S.61A LDA 1991. In this way strategic catchment plans for flood defence can be used to refuse applications for land drainage consent where the proposals are not in accord with the strategic plan. Under common law, riparian landholders have the right to protect property from flooding and land from erosion, however the consent system may still be used to refuse applications that the Agency deems harmful to the environment.

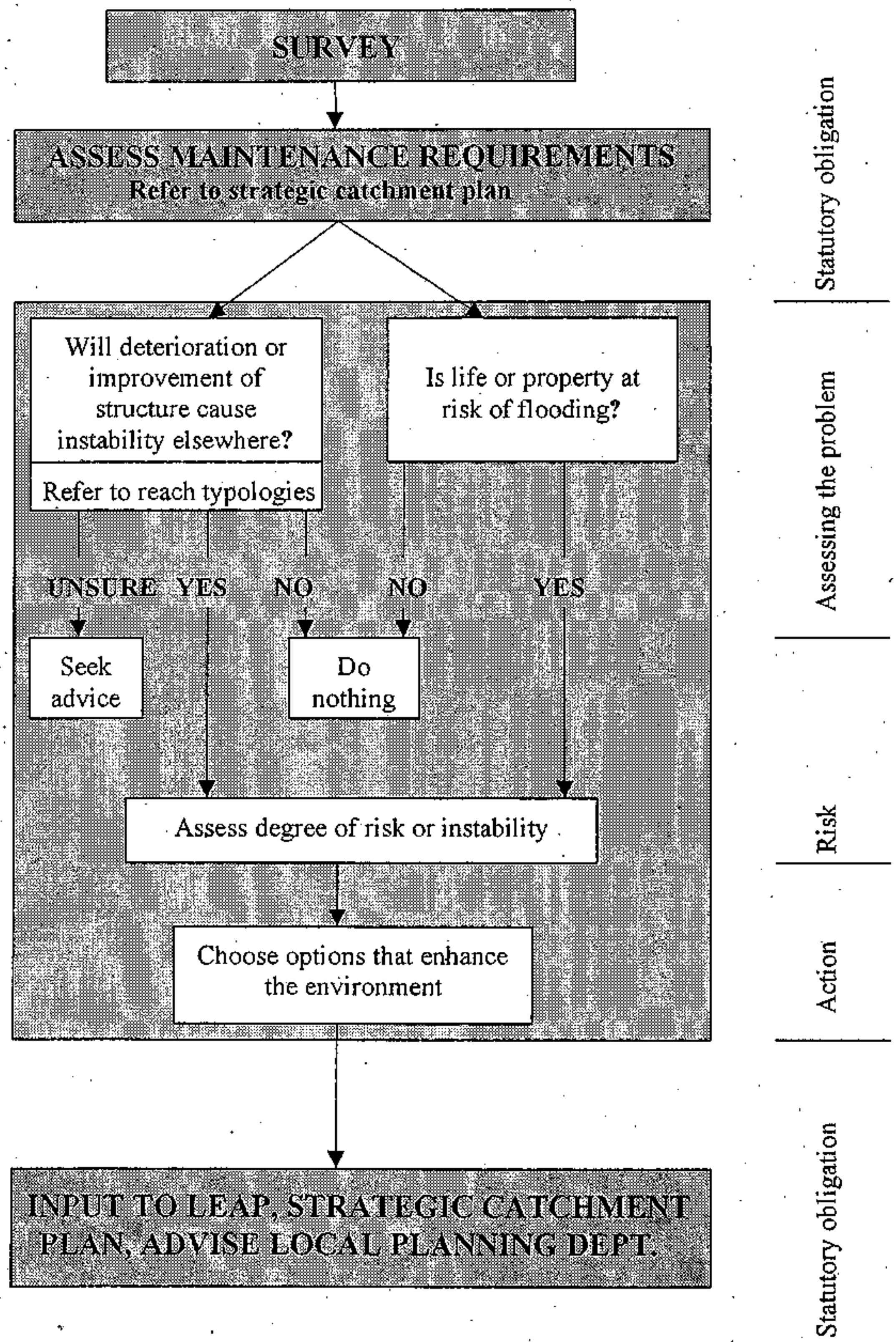
Maintenance operations

Environment Agency policy discussed above, and the supervisory role of the Agency, requires that all maintenance work be conducted within the framework of a strategic plan for flood defence devised for the catchment. To this end the flow diagram shown in Figure 6.1 represents an appropriate decision making process for undertaking maintenance work within such a strategic framework. This framework may also be used in the evaluation of consent applications.

Most commonly in rural catchments, consent applications relate to the control of erosion. The consent system may thus be used to refuse inappropriate proposals for the control of erosion. However the Agency also has a duty to work closely with all sectors of society and to influence, through education and communication, any activity which impacts on the river catchment. Riparian landholders have no obligation to make good any erosion caused by the natural actions of a river. Any action by the landholder that results in erosion does however invoke a responsibility. Since the Agency has no authority to enforce erosion control by riparian landholders a program of bankside fencing for example, cannot be enforced. However an education or local information program, may provide benefits for landholders by reducing loss of land, to the Agency by reducing river instability and to further the aims of sustainable development. Such an information program is entirely within the remit of the Agency under its duty to form links with external groups. An effective information program will also reduce the number of unacceptable applications for land drainage consent. Grants are available to riparian owners through three different agri-environment schemes: Countryside Stewardship, Environmentally Sensitive Area and Set-aside. Relevant information is available from the Farming and Wildlife Advisory Group (FWAG).

There is increasing public interest in river restoration schemes and in some locations the rehabilitation of a previously modified channel may present an opportunity for enhancement of conservation (see NRA Conservation Strategy, 1993). In some circumstances channel restoration may solve problems of channel instability that pose a flood risk. Channels that are designed in an environmentally sensitive way are likely to have reduced costs in terms of maintenance. River restoration can be costly in terms of initial capital investment but when viewed as a long-term solution to existing problems the costs and benefits are likely to be justified. Such schemes may be funded in the usual way for land drainage improvements under S. 147 WRA 1991 through the Ministry of Agriculture, Food and Fisheries (MAFF). River restoration work is entirely in accord with the guidance given to the Agency for sustainable development quoted earlier.

Figure 6.1 Decision making process for flood defence



Under certain circumstances any proposed works may require an Environmental Statement conducted by the proposer of works or an Environmental Assessment conducted by the decision maker. However it is recognised that informal environmental assessment should be built into the planning appraisal and design of all relevant projects. Under its general powers the Agency may require some form of assessment before applications are made for activities such as water abstraction, introduction of fish and works on the bed or banks of rivers (e.g. S.37 EA 1995).

The following two sections present some general principles for consideration in all catchment and river management, and give specific recommendations for long-term catchment wide and short term riparian management of the River Lune.

6.2 LONG TERM AND CATCHMENT WIDE

This study has discussed in some detail the importance of catchment land use for determining the response of rivers. It is clearly not the role of the Environment Agency to dictate the way land is managed however it does have a duty to inform and provide guidance where ever possible. In practice for rural catchments this may be through providing information for organisations such as The Farming and Wildlife Advisory Group or through direct links with local land agents and other farming groups. However useful information can only be provided if the Agency presents a strong catchment management plan of its own. Such a plan should not be based on the individual reach scale proposals of a particular interest group or function of the Agency. Local Environment Agency Plans (LEAPS) go someway towards raising issues important to different groups in the catchment and may present the way forward for discussions when new approaches are felt to be required. The LEAP process is ongoing and although the LEAP for the Lune has already been written it is hoped that the recommendations of this study will be incorporated into the process.

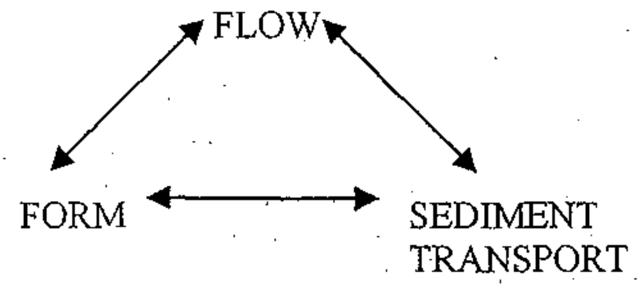
The results presented earlier in this report clearly show that land use has changed the flood characteristics of the River Lune since 1950. This is most likely the result of land drainage activities but may also be as a result of vegetation changes and increased runoff rates. Intensive grazing in the higher parts of the catchment (i.e. above 300 m or 1/3 of the catchment) appears to be having an impact on the runoff response of these areas although increased winter rainfall and increased intensity of rainfall in these areas is particularly important. Rainfall has been more variable over the last two decades than previously this century. A greater percentage of the rain is falling in winter and particularly in early spring; the intensity of this rain is also increasing. Coupled with the runoff response associated with intensive farming practices and land drainage the trend in flood frequency is likely to continue. Predictions of climate change research suggest that these rainfall trends will continue. Concern is increasingly being voiced about the role of fine sediment pollution in British Rivers, particularly with reference to declining fish stocks and river bed compaction and siltation. With increased runoff from upland areas such as the Howgill Fells, which are increasingly heavily grazed, it is likely that the fine sediment load in the Lune is increasing. The role of land use in the behaviour and amount of fine sediment in our rivers is not precisely understood at this time but is the subject of an increasing amount of research.

There are two major implications from the results presented. Firstly the nature of the discharge regime has changed so that the regime is more event based, with more floods and more low flow days. This has obvious implications for flood risk and all the attendant problems of low flows for biological communities, water quality and also water resource. What may be less obvious is that stream power, a specific measure of a rivers ability to erode, is occurring at sufficient magnitudes to cause erosion more frequently. There is no direct evidence of increasing rates of lateral movement in terms of channel migration although cross section morphology may have changed since the sinuosity of the main river Lune, in the widest part of its floodplain, has been declining over the last 150 years. What is clear is that extensive reaches of the Lune are actively eroding their banks. The second major implication is that in all likelihood these climatic extremes will become more severe in future.

In the long-term, solutions to mitigate against the impacts of summer low flows and to reduce the amount and velocity of flood discharges, would be to increase the amount of water storage in the catchment. This may take the form of blocking up moor drains (for which grants already exist) or exploiting natural water storage. Old river channels make ideal wetland areas since they are often inundated during floods. Alternatively wetland areas can be created in areas of natural drainage. Clearly such ventures would have to be carefully located to be self-sustaining. Wetlands can also usefully be located adjacent to river channels and may provide the additional role of acting as buffer strips. The role of buffer strips in filtering pollution is the matter of some debate. However it is likely that such buffer strips will play an important role in filtering fine sediment, they have been widely used for this purpose for pre-afforestation drainage. For general reference and practical application of buffer zones see Haycock et al (1997), published by the Environment Agency.

Discussions with Agency staff during the three years of this project have lead to a number of recommendations having already been taken up as part of an exploratory exercise to find options that will work in this catchment. These have included fencing of river banks, to allow vegetation growth, to a variety of willow staking techniques, these will be discussed in greater detail in the following section. In terms of catchment management it has become clear that bank erosion is a major issue. In many cases this is due to localised heavy grazing of banks and is generally the responsibility of the riparian owner. However extensive areas of eroding bank may be a major source of fine sediment and in some cases coarse sediment in the river system. This is not only a pollution problem in terms of impacts on aquatic flora and fauna but adds to morphological instability in the system and can become, and in some locations is, an issue for flood defence in the following way. As discussed previously the channel morphology is a direct result of the sediment and discharge regime see Figure 6.2. If channel cross section becomes wider as a result of bank erosion, different deposition features are likely to develop and the water depth decreases. If in addition the supply of sediment is increased (e.g. through accelerated bank erosion) instability is further advanced. Depositional areas are likely to increase in number or size and in new locations. This is likely since any change in the sediment regime may lead to morphological adjustment throughout the river system; channel morphology may change in a number of locations not just at the original site of erosion. This has its most obvious manifestation under bridges where it has become necessary to remove gravel to prevent obstruction of the flow.

Figure 6.2 Channel controls and dynamic Interactions



Declining catches in salmonid fish has prompted the development of in-river structures (groynes or croys, boulders etc.) with the intention of creating diverse habitats and pools to improve the catch. This practice is most likely a response not just to declining stock levels but changes in the flow regime and degraded habitat. Caution should be exercised in all such work where erosion is already a problem since any structure that changes the flow pattern in a reach (particularly during high flows) may exacerbate erosion.

Large-scale and long-term solutions are necessary to achieve sustainable development and will reduce the need for short-term, often inappropriate "habitat improvement" work and hard engineering structures. Ultimate goals should be to reduce runoff particularly in upland areas and tributary streams. This may take the form of advising on grants to block moor drains and prevent stock access to stream banks. Clearly the Agency has an advisory role to play in such work. River restoration works should be exploited wherever possible and targeted at the most degraded reaches, i.e. those that have been heavily channelised. The optimum solution is usually to restore channels to their original pattern and cross section, this is not always possible but compromise solutions can be reached provided that robust design criteria are used (see Section 5).

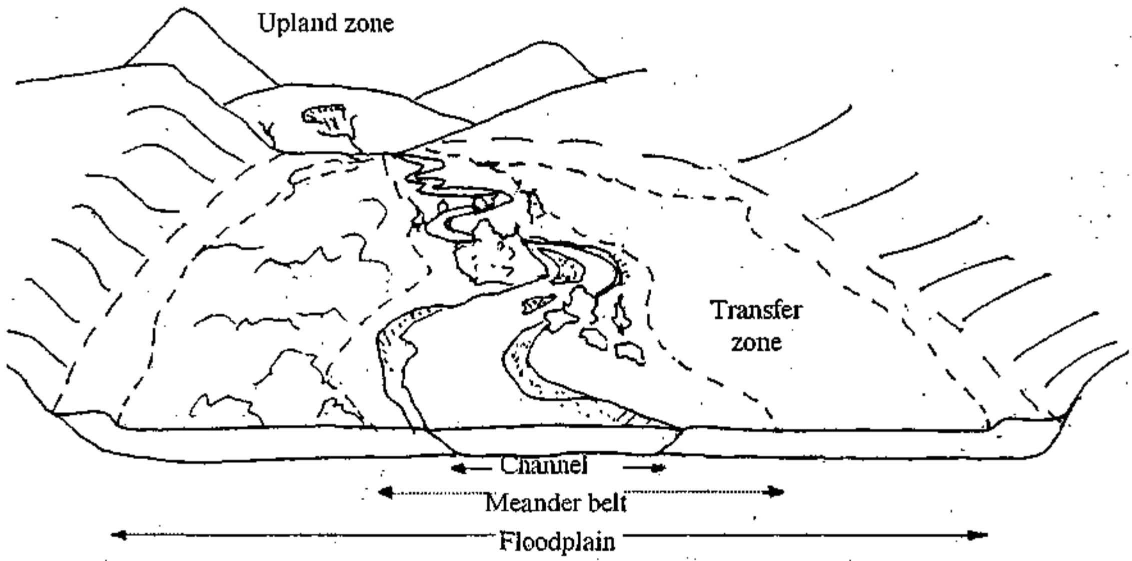
It is important to always maintain a catchment wide view and although the initiation of long-term solutions will necessarily be applied, at least initially in a piecemeal manner, the effects of any work on different parts of the catchment should always be considered. For example, in makes sense to begin a large-scale fencing and bank revegetation program in the upper reaches of the river.

Over the last three years and during the time of this study some bank fencing work has been undertaken to prevent stock access to river banks. This has so far been successful and should be encouraged. However fencing is not the answer to all problems and in many locations the channel should be expected to erode to some degree. Particularly susceptible reaches are the engineered reach above Tebay and that upstream from Arkholme (discussed in Section 5). Attempts to control naturally highly active channels are prone to a high failure rate. Long-term solutions are to allow a certain degree of lateral channel movement. Therefore it may not be appropriate to place stock fencing close to banks (i.e. within 10 m) that may erode quickly; this includes the outer bank of meander bends. An ideal solution would be to have a wide strip of Set-aside land that extends across the width of the meander belt (see Figure 6.3).

Need to explore further.

Recent discussions indicate that the Set-aside scheme is due to become more flexible such that this kind of land could be used. The idea behind this kind of zoning is an extension of the idea for buffer strips and would more appropriately be called a floodplain stability strip. The advantages of floodplain zoning may be particularly relevant on the Lune where fencing is often destroyed or damaged during floodplain inundation.

Figure 6.3 Floodplain zones (modified from Brookes, 1995)



Wherever possible water storage improvements within the catchment will help to reduce flood peaks and perhaps more importantly for this catchment, augment low flows. Wetland creation on floodplain land may not be popular with land owners; however, there may be considerable benefits in placing wetlands close to the main channel within the meander belt by reducing erosion risk. Old river channels are ideal locations for wetlands as these areas are usually inundated during floods and may not be such valuable grazing land. The advantages for water resources and flood defence are equal to the improvements in physical habitat for flora and fauna.

Long-term solutions such as those described above will have major benefits to the Agency in the pursuit of its aims and the operation of its functions but they are likely to be the hardest changes to implement. Considerable advances in catchment management and improvement in other areas have been achieved through the actions and discussions of organisations that encompass all stakeholders within the catchment. Examples of such groups are the Dee Conservation Group, The Urt Rivers Group and the Eden Rivers Trust. It is strongly recommended that a Lune Rivers Group be established. This is not an Agency group but a crucial vehicle for the Agency to pass on its plan for the catchment and to exercise its supervisory and advisory roles.

Suggested points of action:

- Assist in the establishment of a Lune rivers group.
- Investigate opportunities to restore the sinuosity of realigned channels
- Educate riparian landowners as to the benefits of bankside vegetation in controlling erosion and the use of buffer zones.
- Educate landowners on the benefits of blocking moor drains.
- Explore opportunities for creating wetland areas and other potential water storage areas.
- Encourage the development of floodplain zoning to allow channel migration, potentially using agri-environment schemes.
- Monitor changes in channel geometry and stability, particularly where fencing or stock restriction is used.

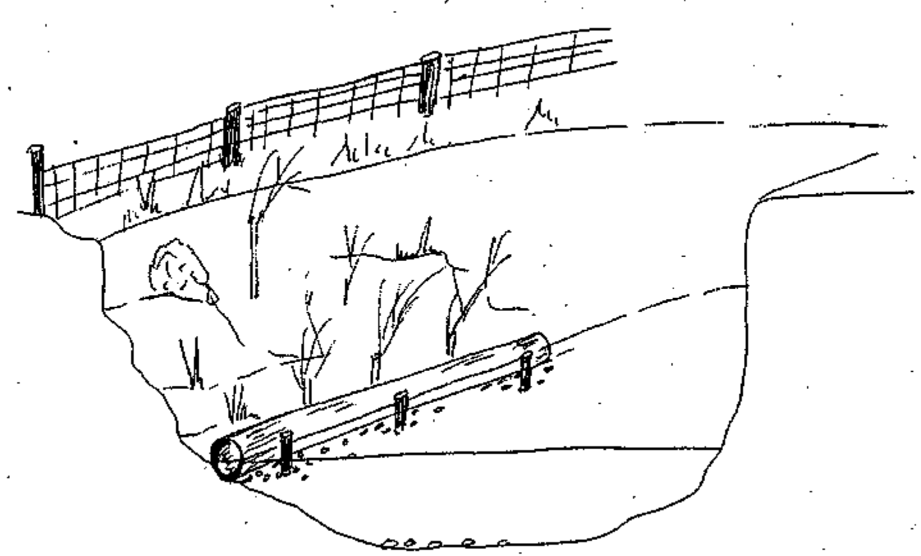
6.3 SHORT TERM CHANNEL MANAGEMENT

A catchment scale approach allows management to be aimed at all contributory factors in the degradation and loss of habitat in rivers. One of The immediate symptoms of river system instability is bank erosion, a natural process that is frequently accelerated by human action. It is likely therefore that the control of bank erosion, whether for flood defence purposes or from the loss of riparian land will continue to be necessary in the short-term. However it is vital that before any work is undertaken, questions should be asked as to whether it is really necessary and whether it will lead to problems up or downstream, see Figure 6.1.

Where it is deemed necessary to alter channel morphology for flood defence purposes or where consent has been granted for land drainage work, consideration should be given to certain key processes. Observation of the morphology of the pre-modified channel, taking account of mid channel bars, point bars, medial bars, confluences, diffluences and bends. Such features are evidence of the sediment and discharge regime of the river and should be preserved wherever possible. Modified channels have traditionally been constructed with trapezoid section, which presents few opportunities for the development of bars and a variety of flow types. Indeed, such channels are often heavily maintained to alleviate 'sediment related problems'.

The majority of past revetment work on the Lune is hard engineered structures that often require maintenance and are unsightly. It is known that treating erosion problems in this way usually transfers the problem elsewhere. There are occasions where it is necessary to protect from erosion for example where property is threatened. In many cases on the Lune the erosion problem is simply one of overgrazing and protection from stock damage and the growth of vegetation are all that is required to slow erosion to an acceptable rate. In such cases fencing or stock exclusion should be the first step. If vegetation growth proves not to be insufficient then some form of revetment may be necessary to protect the bank toe until tree roots are established and the bank becomes stable. This need not take the form of large limestone blocks as has been widely used in the Lune; other possibilities include tree pinning (see Figure 6.4). The advantage of degradable materials is that they will eventually decay and need not be replaced if the bank has stabilised through vegetation growth. On much of the Lune including the main floodplain where stream power to erode is greatest, toe revetment and stock exclusion should be sufficient in all but the most severe cases. Exceptions may include the outer bank of some meanders where tree planting in addition to toe revetment and stock exclusion may be required. It should be noted that willow staking alone has successfully stabilised a number of banks on the Lune. Sites of failure are usually where the stakes have been incorrectly placed and where fluvial action alone is driving the erosion rather than just overgrazing.

6.4 Pinned tree revetment



Steep vertical banks that are freshly cut may indicate an attempt by the river to migrate laterally, this process is harder to control and may only be slowed in the long-term by wide buffer strips as discussed previously. The only way to control erosion is to increase the erosive resistance of bank material or to deflect flow away from the bank. Flow deflection is a harsh engineering solution that should only be considered in the most severe circumstances. Consideration should be given in these circumstances to the location of the reach in question (see reach typologies, Section 5) and the potential cause of the erosion. Bank resistance is very high in on densely wooded reaches; long-term solutions may look towards woodland development at some locations i.e. outer bends of meanders.

It has been discussed previously that the sinuosity of the Lune in its main flood plain has been declining over the last 150 years. This may be in part a response to changing sediment and discharge regime but much of the reduction is related to bankside revetments and channel realignment. It is possible therefore that if sediment loads are reduced by improved land management and reduced stream bank erosion the channel may become more sinuous, highlighting the importance of floodplain zoning to allow some lateral migration. In addition the channel is still responding to channel modifications of the past and may be attempting to extend its channel length and thereby increase sinuosity by developing meanders in new locations. These locations may be characterised by the steep vertically cut banks mentioned in the previous paragraph. In most situations on the Lune complete bank height revetments are not required as long as vegetation can be established. They are unsightly and over-engineered as well as expensive. In addition isolated revetments on a bank face without a good vegetation and root structure binding the soil behind are liable to washout and collapse – such solutions are not sustainable. Rebuilding bank profiles and forcing the channel into a narrower or deeper cross section is also likely to fail and is unsustainable. Reference should be made to the design equations in Section 5. It is also important to design a channel cross section in harmony with the existing channel; this may be done by simply referring to the existing channel both up and downstream. River restoration is a science and an art and should be carefully planned and carried out. Expensive schemes should include supervision in the field, to ensure that contractors accurately construct design channels, this includes the alignment of bank revetments.

Suggested methods for the control of bank erosion:

- Exclude stock where banks are subject to uncontrolled grazing.
- Allow vegetation to become established.
- If erosion is severe willow staking could be considered.
- If vegetation is insufficient to control erosion use toe revetments, ideally pinned trees or other natural materials or local stone as a last resort.
- Bank repairs should be carefully located so that appropriate channel geometry is maintained (see equations in Section 5).

It is not the intention of this report to give detailed guidelines on the construction of alternative methods of erosion control, reference should be made to relevant manuals *and papers, and some examples are listed below:*

- Manual of River Restoration Techniques, available from River Restoration Centre, Silsoe Campus, Silsoe, Beds. MK45 4DT .
- Lewis, G. and Williams, G. Rivers and Wildlife Handbook. RSPB & RSNC; 1984.
- Thorne, C. R.; Hey, R. D., and Newson, M. D., (Eds.) Applied fluvial geomorphology for river engineering and management: John Wiley & Sons; 1997.

6.4 Geographic Information Systems (GIS)

The only effective method for displaying large spatial databases is GIS. All the spatial data presented in this report i.e. maps, channel changes, location of erosion and engineering structures, is held on an ARCINFO system. This data is easily converted to ARCVIEW, which is likely to be available at most EA offices in the very near future. The use of GIS will greatly assist long-term catchment planning, as all relevant information is immediately accessible for any location. The maps in Figures 6.5 and 6.6 are 2D and 3D maps of the catchment, the extent of flat floodplain land can immediately be visualised and should indicate sites where lateral channel migration may occur and where the benefits of floodplain zoning would be greatest. Any new or updated information can easily be added to the database including information from fisheries and ecology on habitat information and sites of abstraction etc. Maps illustrated particular issues are easily produced by querying relevant subsets of the database. It is strongly recommended that the information compiled for this project be utilised for future management in the form of a GIS.

Figure 6.5 2D view of catchment

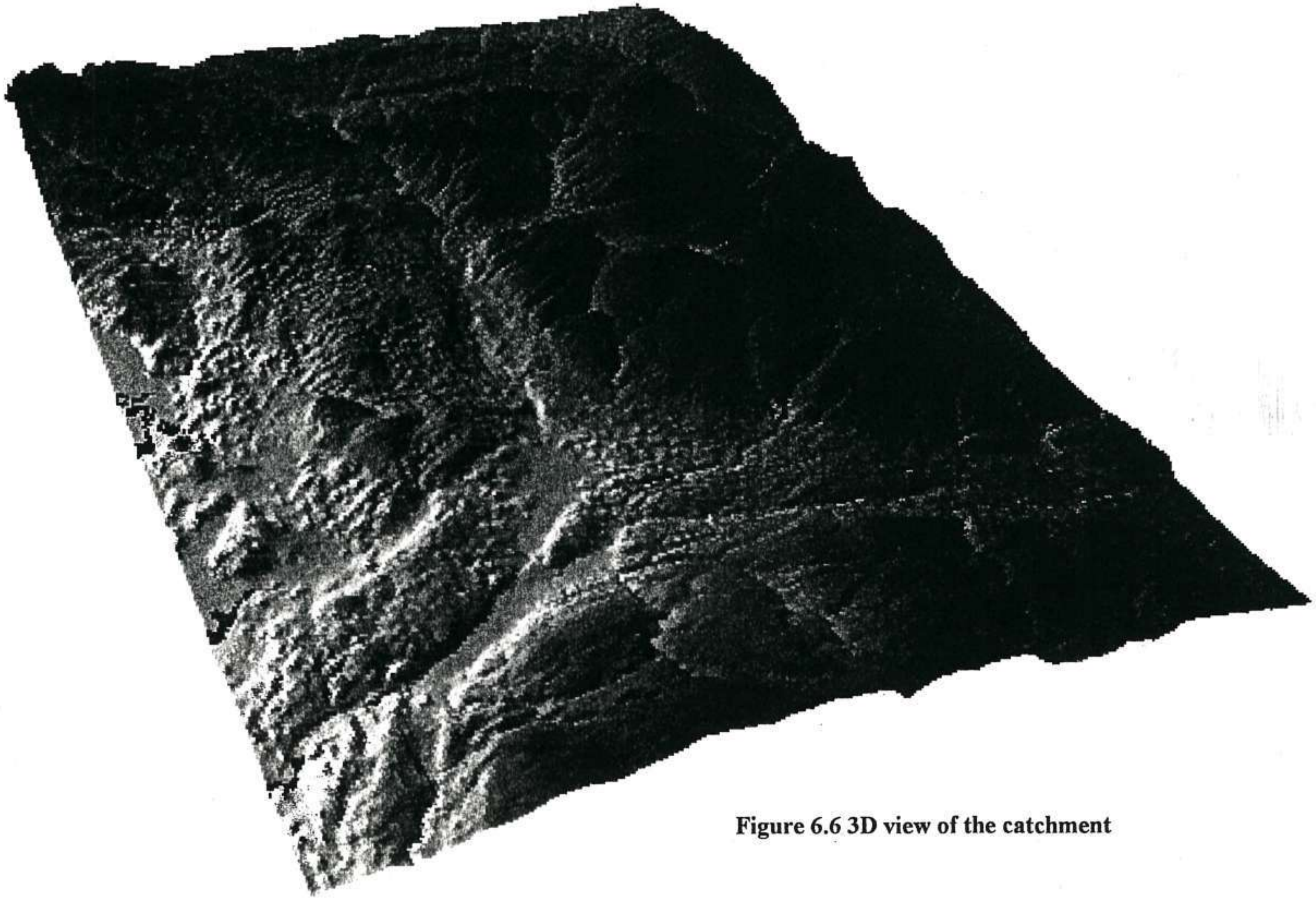


Figure 6.6 3D view of the catchment

6.6 Discussion

This study has clearly shown that the River Lune is in a degraded state both in terms of the intensive grazing and drainage of the catchment and the state of the river channels. Habitat quality in many locations is poor, erosion is extensive and severe in some locations and geomorphic instability is exacerbating erosion issues. Instability has lead to sediment related flood defence problems and frustration on the part of fishing clubs who have attempted often damaging "habitat improvement" works.

Existing problems are largely as a result of land use changes over long periods of time, however recent climatic variability has resulted in many of the problems being accelerated. Predictions of future climate suggest that recent extremes of weather will continue and become greater.

The implications of this study are clear, the catchment and its river channels cannot sustain the current land use activities and is unlikely to withstand the impacts of future climate in its current state. However long-term solutions exist that will protect the river from further degradation and the potentially destabilising effect of climate change. It is essentially that catchment management is implemented in its true sense, it is necessary that changes be made by those who manage the land with advice from expert bodies. To this end, some form of catchment group should be established, this may be initiated by the Environment Agency under its supervisory and influencing roles however it should be clear that stakeholders in the catchment will drive any action. An often heard criticism of river groups is that they tend to be dominated by a particular interest group and that any action is slow to be implemented. Care should be taken in ensuring that a representative balance of members is made and that all members are included so that all views are heard. The process may be slow but solutions are likely to be more acceptable and sustainable in the long-term. In summary, the Agency should not be seen to be isolationist and imposing policy on an already troubled farming community.

Monitoring has been highlighted as an essential component of river restoration and assessments should be made of any works undertaken rather than assuming that any job completed has been successful. It has become clear in the River Lune that many of the soft-engineering options used in other rivers are unsuccessful due to the high stream power. In some cases bank protection work has been unsuccessful through inappropriate design and implementation. All successes and failures should be recorded and an attempt made to understand the reasons of failure of some structures. It is also important to note where in the system solutions have failed and to identify changing reaches or migrating meander bends and new areas of instability.

This report attempts to provide information and tools to support the operations of flood defence by encouraging understanding of fluvial geomorphic and sedimentary processes. However it should be understood that a thorough grasp of the subject is not achieved through the means of one study. The role of flood defence has become more diverse over recent years and the need for training and the inclusion of the discipline of fluvial geomorphology is apparent. In addition it is not possible to produce a manual to cover all eventualities and describe appropriate action for all scenarios. This report is given as guidance and to provide information, there will always be circumstances where expert opinion and advice should be sought.

6.7 Summary

The implications of this study are clear, the catchment and its river channels cannot sustain the current land use activities and is unlikely to withstand the impacts of future climate in its current state.

The Environment Agency has the remit to promote sustainable development and catchment management; potential solutions are presented for the long-term management of the Lune. Recommendations include: establishing a Lune rivers group, restoration of realigned channels, educating riparian landowners as to the benefits of bankside vegetation in controlling erosion and the use of buffer zones and monitoring changes in channel geometry and stability, particularly where fencing or stock restriction is used. In addition the Agency can educate landowners on the benefits of blocking moor drains, explore opportunities for creating wetland areas and other potential water storage areas and encourage the development of floodplain zoning to allow channel migration, potentially using agri-environment schemes.

It is recommended that short-term management options for the control of bank erosion should exclude stock where banks are subject to uncontrolled grazing and allow vegetation to become established. If erosion is severe willow staking could be considered, where vegetation is insufficient to control erosion toe revetments could be used, ideally pinned trees or other natural materials or local stone as a last resort. Bank repairs should be carefully located so that appropriate channel geometry is maintained.

"Nature has not only demonstrated how to erode but also how to protect,
there is no protective measure used by man that was not invented by nature."
Bache et al (1981)

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APPENDIX 1 TIME SERIES ANALYSIS METHODS

The results of time series analysis presented in the body of this thesis are the output from microCAPTAIN, software written by Wlodek Tych, the methods used are those described in Young et al (1998) and developed by the authors. The methods employed represent the latest developments in the analysis of nonstationary time series that are particularly useful for adaptive seasonal adjustments and extraction of signals at different stages of the spectrum. The methods described are applied in a novel way to the problems presented in this thesis. It is the intention of this section to give a general description of the methods used and the order of the analyses undertaken to produce the various results presented in the text. It was considered inappropriate to describe in detail the software used but sufficient information is presented which illustrates the novelty of this software.

Introduction and background from Young et al 1998

Many environmental time series exhibit periodic, seasonal or cyclical effects of various kinds. For instance, both climate and socio-economic phenomena are influenced by annual seasonal variations; life cycles display both diurnal and annual rhythms. In order to investigate such periodic or quasi-periodic phenomena and perform functions such as forecasting, interpolation over gaps or seasonal adjustment, one needs to estimate the periodic components in some manner. This estimation problem is complicated by the fact that the periodic variations which affect real time series are often nonstationary, in the sense that their amplitude and phase tend to change over the observation interval. Many identification and estimation procedures have been suggested for handling such nonstationary periodicity but some of the most powerful originate in the statistical and econometrics literature, where the estimation problem is often termed *signal extraction*.

One of the oldest and best known techniques for signal extraction is the Census X-11 method (Shiskin *et al*, 1967) and its later extensions X-11 ARIMA, and X-12 ARIMA (e.g. Dagum, 1980,1988; Findley *et al*., 1992, 1996). This is a rather *ad-hoc* method of seasonal adjustment in which smoothing procedures, such as the Henderson family of centralised moving average filters, are used to extract trend and seasonal components from the time series. The design of these filters is based mainly on previous experience and they have been continuously refined as the method has been applied to more and more series. However, the X-11 family of techniques have been extremely popular and are used by the national statistical services of many countries for the routine seasonal adjustment of socio-economic time series.

Three other important approaches to signal extraction has been developed in recent years. All of these are based on the concept of an *Unobserved Components* (UC) model, in which the time series is assumed to be composed of an additive or multiplicative combination of different components that have defined statistical characteristics but which cannot be observed directly.

- The *ARIMA* or *Reduced Form* approach to UC model identification and estimation follows from the success of Box-Jenkins methods of time series analysis and forecasting and is based on the assumption that the series can be modelled as an ARIMA model (the 'reduced form' in econometric terms) and the unobserved components are obtained by reference to the relationship between the ARIMA and UC models. Such identification procedure requires the imposition of a number of (arbitrary) restrictions to ensure the existence and uniqueness of the decomposition.

- The *State Space* (SS) approach provides a more obvious formulation of unobserved component concepts. Here, the UC model is considered as the observation equation of a discrete time stochastic SS model and the associated state equations are used to model each of the components in Gauss-Markov (GM) form. This formulation has its origin in the 1960's when control engineers realised that recursive estimation and, in particular, the *Kalman Filter* (KF), could be applied to the problem of estimating time variable parameters in regression models, usually within a dynamic systems context (see e.g. the papers of Young, 1969, 1974 which review the early literature on this topic and discuss the first author's prior contributions to time variable parameter estimation applied to both continuous and discrete-time data). More recent developments have shown how this approach can be extended in various ways to problems of forecasting, backcasting, smoothing and signal extraction.

- The *Optimal Regularisation* approach is based on direct optimal estimation of the components within a regularisation context where constraints are imposed on the state estimates via a Lagrange Multiplier term within the cost function, in order to ensure that they possess the required characteristics. More specifically, the variance of residuals is usually minimised subject to a given degree of smoothness imposed on the components, as defined by specified weighting matrices in the Lagrange Multiplier term of the cost function. The values of Lagrange Multipliers are estimated in different ways, such as cross validation, but Akaike estimates them within a Bayesian framework.

The *Dynamic Harmonic Regression* (DHR) model considered in this paper is of the UC type and is formulated within the stochastic SS setting. However, it is important to stress that this approach can yield asymptotically equivalent results to Wiener-Kolmogorov filtering and Regularisation if the models on which they are all based are made compatible. This means that the main differences between the methods quoted above are not necessarily the results they achieve but the way in which they attack the problem of signal extraction and the computational manner in which they solve this problem. However, the SS formulation seems to the authors (see Young and Pedregal, 1996) not only more natural and satisfying but also more attractive computationally because it so nicely integrates the processes of forecasting, interpolation and seasonal adjustment into a single recursive framework. To paraphrase Wiener (1949), it seems to provide a rather natural approach to the "extrapolation, interpolation and smoothing of *nonstationary* time series". The main difference between the DHR approach and related techniques, such as Harvey's Structural Modelling method, lies in the formulation of the UC model for the periodic components and the method of optimising the hyper-parameters in this model.

Methods of analysis used in this study

The suite of techniques used offers a flexible approach based on a Dynamic Harmonic Regression (DHR) model of the unobserved components (UC) type. The model is particularly useful for adaptive seasonal adjustment, signal extraction, interpolation over gaps, as well as forecasting (or backcasting) of nonstationary time series.

The Kalman Filter (KF) and Fixed Interval Smoothing (FIS) algorithms are exploited for estimating the various components, with the Noise Variance Ratio (NVR) and other hyper-parameters in the stochastic state space model estimated by a novel optimisation method in the frequency domain. This optimisation is based on a cost function defined in terms of the difference between the logarithmic pseudo-spectrum of the DHR model and the logarithmic autoregressive spectrum of the time series. In all of the applications considered, this cost function not only seems to yield improved convergence characteristics when compared with the equivalent Maximum Likelihood (ML) function, but it also has much reduced numerical requirements.

Steps in analysis of rainfall and runoff data

Data are subjected to a low pass filter (IRWsmooth) to avoid distortion then every 14^{th} sample is selected. This results in data that are decimated to two week intervals, which represents a smoothing operation and reduces the size of the data set.

The data are then optimised using the Noise Variance Ratio (NVR) and finally the Dynamic Harmonic Regression (DHR) is applied.

Different elements of the model are then extracted and plotted graphically. These include fast and slow components of the data that may not be obvious through observation of the raw data.

Trends produced by the DHR in the rainfall and runoff data can then be compared to assess changes in the runoff response.

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