River response to recent environmental change in the Yorkshire Ouse basin, northern England.

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The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others

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ABSTRACT

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This study examines historical variations in flood frequency and magnitude in the Yorkshire Ouse basin, northern England, over the last 900 years. The causes of temporal and spatial variations in flooding are evaluated through investigation of climatic and land-use controls.

Documentary evidence of flooding and climate suggests that a series of large floods between 1263 and 1360 were associated with climatic deterioration from the Medieval Optimum. A shift to generally milder conditions between 1361 and 1549 resulted in no floods being documented in the Ouse basin The frequency of large magnitude floods increased dramatically between 1550 and 1680, as a result of low temperatures, increased surface wetness, more frequent snowfall and a southward shift of prevailing storm tracks over middle latitudes, associated with the onset of the 'Little Ice Age'. In contrast, during a warmer phase of the Little Ice Age, between 1681 and 1763, the frequency of localised summer flooding increased in the Ouse basin due to more frequent high intensity, short duration convective storms. Extensive lowland flooding became more common between 1764 and 1799 due to an increase in heavy rainfall, followed by a 50-year period characterised by relatively moderate flood frequencies and magnitudes. The later half of the nineteenth century experienced high flood frequencies and magnitudes, particularly in the 1870s and early-1880s, coinciding with high rainfall totals and a high incidence of cyclonic flood generation.

Gauged flood and climate data, and land-use records indicate that the period between 1900 and 1916 was characterised by very low flood frequencies and magnitudes, associated with low rainfall, warm temperatures, and an increase in westerly flood generation. Between 1916 and 1943 there were marked variations in flood magnitude between the rural northern rivers and southern industrialised rivers. Magnitudes generally increased on northern rivers, whilst on some southern tributaries of the Ouse, flood magnitudes declined as a result of widespread channel improvement and flood defence schemes. Around 1944 a marked and sustained increase in flood frequency on northern rivers was associated with an increase in the incidence of heavy daily rainfall, greater westerly flood generation and large-scale upland and lowland drainage. Very low flood frequencies and magnitudes between 1969 and 1977 resulted from extremely low rainfall totals. Whereas the most recent period, between 1978 and 1996 has experienced some of the highest flood frequencies and magnitudes on record, associated with an increase in the frequency of floods generated under cyclonic and south-westerly synoptic situations, and a number of land-use changes promoting more rapid runoff including, large increases in upland livestock numbers, an increase in the area under winter-cereals and the cumulative effects of moorland gripping.

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LIST OF ABBREVIATIONS

AFF	Annual flood frequency
AM	Annual maximum
AME	Annual mean exceedance
CA	Catchment area (km^2)
CET	Central England temperature record
EA	Environment Agency
EWP	England and Wales precipitation record
H_o	Null hypothesis
IH	Institute of Hydrology
LOEPS	Land-Ocean Evolution Perspective Study
LOIS	Land-Ocean Interaction Study
MAFF	Ministry of Agriculture, Fisheries and Food
M_T	Amount of daily rainfall with a return period of T-years
NRA	National Rivers Authority
POT	Peaks over threshold
Q	Peak flood discharge, usually in cumecs (m^{3}s^{-1})
Q_T	Peak discharge of a flood of T-years return period, usually in cumecs (m^{3}s^{-1})
T	Return period in years
UC	Useable capacity of a reservoir (10^{3}m^3)

CHAPTER 1

INTRODUCTION

1.1. THE LAND-OCEAN INTERACTION STUDY (LOIS)

This research has been undertaken as part of the NERC funded Land-Ocean Interaction Study (LOIS), whose main objective is to 'quantify the exchange, transformation and storage of materials at the land-ocean boundary, and to determine how these parameters vary in time and space' (NERC, 1994, p iv.) Within LOIS there are four main components :

1. Rivers, Atmosphere, Coasts and Estuaries Study (RACS), with three sub-components :
    i. River Basins - RACS(R)
    ii. Atmosphere - RACS(A)
    iii. Coasts and Estuaries - RACS(C)
2. Land-Ocean Evolution Perspective Study (LOEPS)
3. Shelf Edge Study (SES)
4. North Sea Modelling Study (NORMS)

Within each of these components there are two 'interdependent elements', the *Special Topic Programme* and the *Core Programme*. The Special Topic Programme has funded almost seventy research projects by NERC laboratories and UK universities, whilst the Core Programme provides support such as laboratory facilities, staff, and co-ordination of coring operations. This research project has been funded as part of LOEPS Special Topic 12 and has sought to evaluate 'Holocene and historic environmental change in the Yorkshire Ouse and Tees basins and assess its influence on sediment and chemical fluxes to east coast estuaries and the coastal zone'. There were three main aims of this project :

1. To investigate Holocene alluvial histories and environmental change up to 300 *BP*.
2. To evaluate river response to environmental change over the documentary and instrumental period.

3. To undertake mineralogical and geochemical studies to investigate patterns and controls of metal dispersal and storage

This thesis focuses on the second of these aims, whose primary objectives are outlined below.

1.2. RESEARCH OBJECTIVES

This thesis examines historical variations in flood frequency and magnitude, and the climatic and land-use controls of flood hydrology in the Yorkshire Ouse basin, northern England. It has three main objectives :

1. To establish a database of instrumental (last 100-years or so) and documentary (last 900-years or so) records of flooding, climate and land-use in the Yorkshire Ouse basin.

2. To assess spatial and temporal variability within Ouse basin flood records.

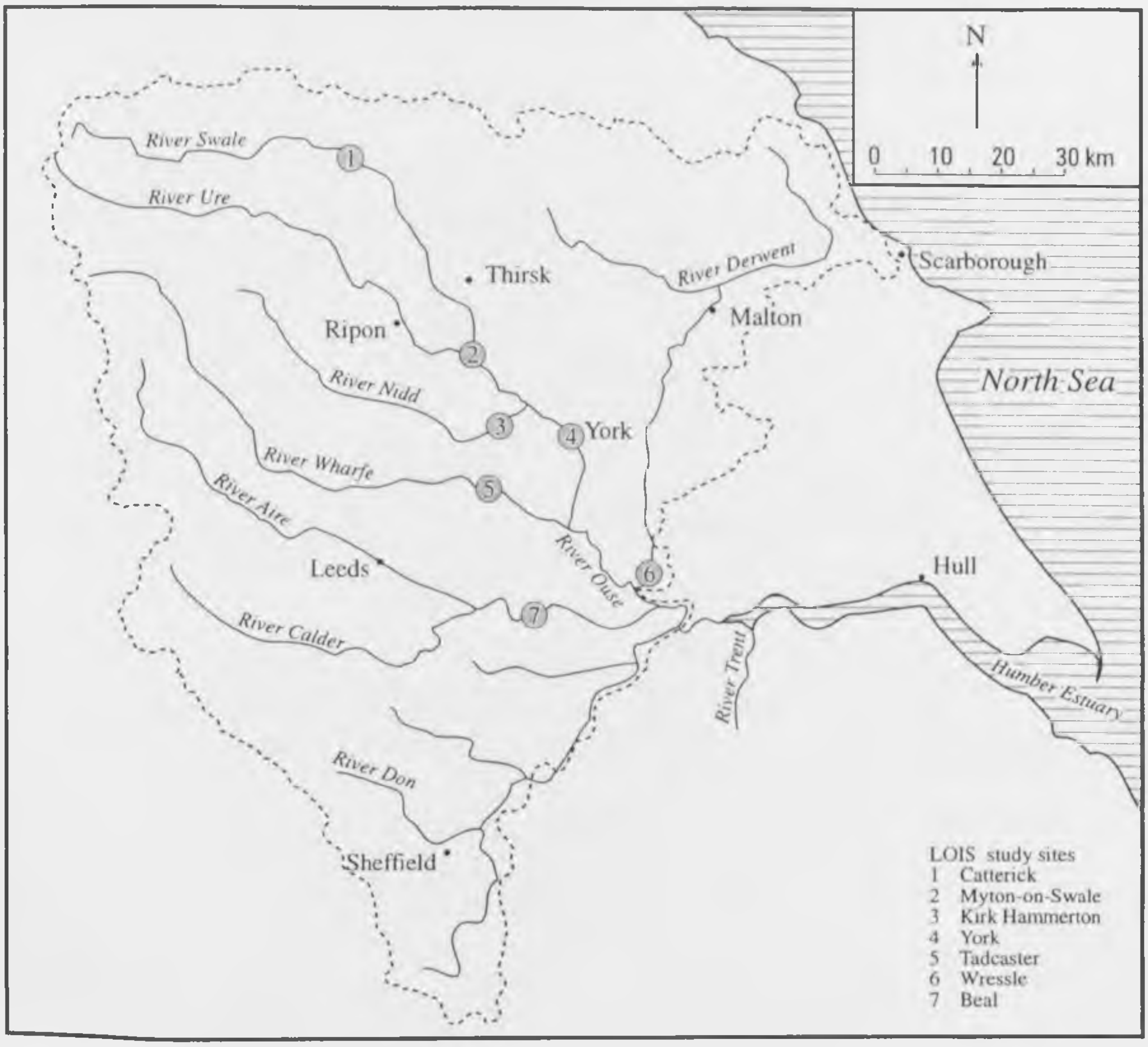
3. To establish whether variations in flood frequency and magnitude coincide with basin scale alterations in land-use change, and/or hydroclimate reflecting changes in upper atmospheric circulations

1.3. RESEARCH SCALE

Spatial Scale

As part of the RACS(R) core programme, a network of flow and water quality monitoring stations were established in the Yorkshire Ouse basin in 1993. These stations were designed to provide data on river discharges and fluxes of sediments, metals, nutrient and organic microcontaminants (NERC, 1994) in the middle and lower reaches of major Ouse tributaries. Consequently, seven short (1-2 km) river reaches were selected (figure 1.1) in close proximity to these sites for detailed investigations into Holocene floodplain development, as part of LOEPS Special Topic 12, to provide a longer-term perspective for contemporary sediment fluxes and storage. With respect to this thesis, the location of flood gauging sites chosen for analysis was restricted to the middle and lower reaches of the non-tidal Ouse basin, close to the study reaches used for the investigation of Holocene alluvial histories. Climate and land-use records, however, were collected (where available) on a basin-wide scale.

Figure 1.1: *Location of Holocene investigation sites*



Temporal Scale

In order to complement the longer-term Holocene alluvial study, the most appropriate timescale for investigation was the documentary period. This is usually considered to span the last 300-400 years, although in the Ouse basin records of flooding have been compiled from as early as the tenth century, a period spanning some 900 years. This time period encompasses some significant climatic episodes including, cooling after the Medieval Optimum, the Little Ice Age and the recent ameleoration of climate (i.e. twentieth century), which can all be examined in terms of flood response. The climatic ameleoration following the Little Ice Age (*c.* 1850) is of particular significance given the predicted increases in future temperature (e.g. Raper *et al.*, 1997), and may be used as an analogue of flood response to a warming climate (Rumsby, 1991). Instrumental records of flooding, climate and land-use change become available towards the end of the nineteenth century and allow for more detailed examination of trends and linkages. Furthermore, the instrumental period coincides with the onset of major anthropogenic modifications of river channels, floodplains and catchments, which can be investigated in conjunction with climatic variation

1.4. RESEARCH STRATEGY AND THESIS STRUCTURE

This project was carried out in four principal phases :

(1) Data collection

Given the lack of an environmental database in the Ouse basin the initial phase of this project was to assess and collect all available data. Three main databases have been established from a variety of sources, (i) flood history (ii) climate history, and (iii) land-use history. Instrumental data have been obtained from a large-number of government and professional sources, whereas documentary evidence has been compiled largely from extensive archival research. These series were then examined in phase two.

(2) Analysis

The main aim of this phase was to examine spatial and temporal variations in flood frequency and magnitude, climate and land-use change. Flood records are analysed using various time series statistical techniques and flood frequency analysis during the instrumental period, and through establishing and examining flood frequency and magnitude data for each lowland tributary during the documentary period. Climate series analysed include rainfall, temperature and atmospheric circulations using similar techniques to those outlined above. Finally, the spatial and temporal variations in land-use changes are considered.

(3) **Development**

The next phase attempted to develop a methodology for investigating synoptic flood generation in a river basin. This allowed for the examination of the relationship between hemispheric-scale atmospheric circulations and flooding in the Ouse basin.

(4) **Integration**

The final phase of this research strategy was the integration of flood, climate and land-use records over the last 900 years, so as to identify key linkages between climate and land-use changes and variations in the flood record.

Chapter 2 reviews three aspects of the flood-related literature, (i) recent trends in UK flooding (ii) the climatic controls, and (iii) the land-use controls of flooding. Background information relating to the Ouse basin is presented in Chapter 3. This is followed by three chapters (4, 5, and 6) investigating variations in flooding, climate and land-use change respectively in the Ouse basin. Chapter 7 provides an integrated overview of flood response to environmental change in the Ouse basin, and Chapter 8 presents the principal conclusions of the study.

CHAPTER 2

REVIEW OF LITERATURE :

Recent trends in flood frequency and magnitude in the UK : climatic and land-use controls

2.1 INTRODUCTION

The main aim of this literature review is to outline the mechanisms by which changes in climate and land-use can affect flood frequency and magnitude. The chapter has three main sections, the first outlines observed variations in flood records in several areas of the UK over the past few hundred years or so. The second and third parts of this chapter consider in detail, how climate and land-use respectively, may influence flood hydrology.

2.2 RECENT TRENDS IN UK FLOODING: 1750-1995

This section reviews temporal trends identified in flood studies for several regions of the British Isles, namely, Wales, Scotland, and northeast England. In these areas both gauged and documentary flood records have been analysed for large numbers of rivers, to examine variations in flood frequency and magnitude. Examples are also considered in Ireland and Southern England.

One of the first studies that investigated long-term changes in flood frequency and magnitude in the UK was that of Howe *et al.* (1967), on the Upper Severn and Wye in mid-Wales. Analysis of a flood stage record for Welsh Bridge at Shrewsbury, suggested that the periods between 1840-1880 and 1940-1964 were characterised by high flood frequency and magnitude. The intervening period was a time of relatively low flood frequency and magnitude. These authors attributed the post-1940 increase to a rise in the incidence of heavy daily rainfalls or storm events, but also conceded that land-use change, particularly pre-afforestation land drainage had ‘aggravated’ the flood problem. Two later studies (Walsh *et al.*, 1982; Higgs, 1987b) both agree that a re-evaluation of the Shrewsbury flood record suggests that the increase in flood frequency dates from the 1920s rather than the 1940s. These new data coincide with a marked and sustained increase in flood frequency on the River Tawe in the Swansea Valley since the

1920s (Walsh *et al.*, 1982) However, in this case the authors suggest that this basin was not affected by land-use changes, since the catchment is predominantly covered by grassland. This increase in flood frequency does coincide with an increase in heavy daily rainfall in South Wales.

Some of the most recent flood studies in Wales have been conducted by Higgs (1987a; 1987b; 1987c) who updated and expanded the earlier work of Howe *et al.* (1967). Higgs showed that there had been a general decline in flood magnitude since 1968 at Bewdley (record length 1921-1983) which coincided with the construction of Clywedog Dam. However, over the same period (1968-1983) flood frequency increased. The decline in flood magnitude was attributed to a decline in winter precipitation, and the increase in flood frequency to agricultural land-drainage and pasture improvement. Higgs also demonstrated that the effects of Clywedog Dam were negligible as far downstream as Bewdley. Using return period analysis Higgs showed that 'even including the post-1968 decline in flood levels, the period since 1940 as a whole has witnessed a general increase in magnitudes and frequencies on the Severn' (Higgs, 1987b, p137.).

In Scotland flood studies have been undertaken over two main timescales. Detailed documentary flood histories have been compiled for the upper Dee and the middle Tweed areas (McEwen, 1986; 1987b; 1989, 1990). Whereas later studies have investigated more recent, shorter-term variations in flood frequency and magnitude (Black, 1996; Grew, 1996; Grew and Werritty, 1995) and flood seasonality (Black, 1992; Black, 1994; Black and Werritty, 1993; 1997).

Over the documentary period (since *c.*1750) historic flood chronologies were established (see McEwen (1987a) for data sources) for the upper Dee above Craithie (McEwen, 1987b; 1989) and for the middle Tweed at Kelso and its tributaries, the River Leader, River Teviot and Whiteadder Water (McEwen, 1990). On the upper Dee three major floods were recorded in the late eighteenth century (1768, 1782 and 1799) all of which were caused by summer frontal storms. Indeed, the most extreme flood on record in the upper Dee, in August 1829 was also generated by summer storms, as were two of the three largest floods in the middle Tweed (August 1294 and August 1948). McEwen found that there had been a change in flood seasonality before and after 1900. Prior to 1900 floods generated by summer frontal storms were more common on the Dee, and associated with a higher flood frequency between 1850 and 1899. Between 1900 and 1976 flood frequency was lower, allied with an increase in winter flooding. In the former period, McEwen also suggests that snowmelt floods were common on both the middle Tweed and Upper Dee associated with the later stages of the 'Little Ice Age'. During this period there was also clear evidence of a cluster of moderate to extreme magnitude floods in the 1870s on the upper Dee, and between the 1870s and 1890s on the middle Tweed, particularly on the Teviot and Whiteadder. McEwen suggests that this peak in magnitude coincided with an increase in the frequency of moderate to extreme rainfall events.

Recent studies of flooding in Scotland have focused on examination of gauged flood records, typically 20-30 years in length. The most detailed and comprehensive study into variations in flood frequency and magnitude in Scotland is that of Grew (1996), who analysed in excess of 130 peak-over-threshold (see section 4.2.1.) flood records. Using time series techniques high flood frequencies were identified in the 1950s, 1980s and 1990s, with the late 1960s and 1970s experiencing relatively low flood frequencies. Patterns in flood magnitude proved more difficult to characterise, however a common pattern in the majority of records was a marked decline in flood magnitude during the early 1970s. However, examination of annual maximum and peak-over-threshold flood records pre and post-1988, in fifteen of the largest river basins in Scotland, have revealed that, 'Many Scottish rivers have registered new maximum floods since 1988, along with increases in the frequency of high flow occurrence and increases in annual runoff' (Black, 1996, p463.). This increase in major flooding is particularly evident in westerly catchments, although no evidence was found of a similar relationship in England and Wales, suggesting variations in seasonal precipitation between the areas (Black, 1996).

In northeast England documentary flood histories since the mid-eighteenth century have been evaluated for the Tyne basin (Macklin *et al.*, 1992b; Passmore *et al.*, 1993; Rumsby, 1991; Rumsby & Macklin, 1994). It was found that the period between 1760 and 1799 was characterised by a high frequency of extreme magnitude floods (>20 year return period). Four events were estimated to have return periods in excess of 100 years (December, 1763, November 1771, March 1782 and July 1792). The largest of these events occurred in November 1771 and Archer (1993) has suggested that this may be the largest flood ever to have occurred in Britain (discharge estimate of 3900 m^3s^{-1} ± 780 m^3s^{-1} at Hexham). Large floods were also common between 1875-1894 and 1955-1969. Periods characterised by more moderate floods (5-20 year return period) occurred between 1820-1874 and 1920-1954. Low flood frequencies and magnitudes were evident between 1800-1819, 1895-1919 and in the 1970s. The most recent period has experienced an increase in severe flooding with large floods on the Tyne in 1986, 1990, 1991 and 1992.

In contrast to the relatively unmanaged Tyne basin (Rumsby, 1991), the River Thames has been subject to many large-scale improvement schemes that have increased the carrying capacity of the channel, particularly since the nineteenth century (NERC, 1986). In a recent study Crooks (1994) analysed peak water levels at 44 locks over a 200km stretch of the River Thames from the 1890s using cumulative deviations from the mean. It was concluded that there has been a constant rate of flood events exceeding bankfull since the 1890s, although a higher frequency of extreme floods occurred prior to 1940. This was attributed to higher intensity rainfall during this period, and the fact that flood prevention schemes and channel dredging caused a localised decline in flood magnitude and event duration. Despite this conclusion, analysis of the daily discharge record at Teddington on the Thames (gauged since 1883) suggests that the three largest floods occurred in November 1894 (1059 m^3s^{-1}), March 1947 (714 m^3s^{-1}) and September 1968 (600 m^3s^{-1}).

Finally, two studies in Ireland have also documented flood histories to assess variations in flood frequency. However, both rivers are situated in tidal reaches and are subject to floods caused by tidal surges. Tyrrell and Hickey (1991) compiled a documentary flood chronology from local newspapers for the River Lee in the City of Cork in Ireland, for a 148 year period from 1841 to 1988. The variability of flood frequency is examined in terms of climatic, riverine and tidal influences. It was concluded that flood frequency steadily increased from the 1840s until the 1920s when there was a dramatic rise. Peak frequencies occurred between 1925-1940 and 1953-1966, and have shown a relative decline in the 1970s and 1980s. Rainfall was shown to be the principal cause of most floods, however combinations of rainfall and tidal conditions were also shown to be significant, with the tidal influence becoming more important from the 1930s to 1960s. In Northern Ireland, Prior and Betts (1974) compiled a documentary flood history for the River Lagan at Belfast between 1906 and 1972. 202 flood events were identified which caused disruption to traffic and damage. Flood frequency was found to be very high between 1906-1921, after 1921 there was a marked reduction in flood frequency, the opposite of the trend shown on the Lee at Cork. High flood frequencies were again common between 1938-1942 and 1953-1961.

In summary it would appear that the timing of major variations in flood frequency and magnitude is often synchronous for a number of river basins. A series of major floods occurred on both the Dee and the Tyne in the late eighteenth century, though the three major floods on the Dee were all caused by summer frontal storms, whereas those on the Tyne occurred in winter, spring and summer. Flood magnitudes were again high between the 1870s and the 1890s on the Dee, the Tweed and the Tyne. There is also evidence of increased flood frequency and magnitude on the River Severn, although Howe *et al.* (1967) suggest this increase occurred between 1840 and 1880. A marked rise in flood frequency has been documented on several rivers around 1920. Around this time the frequency of floods increased on the Tyne, the River Lee, and the Severn and Tawe in Wales In contrast flood frequency declined markedly on the River Lagan at Belfast around the 1920s. Evidence of increased flood frequency between the 1950s and early 1960 can be seen in Scotland and Ireland, and extremely low flood frequencies and magnitudes in the late-1960s and 1970s are evident on every river. Similarly, the recent increase in flooding during the late 1980s and 1990 is clear in both Scotland and northern England

Rivers that have been subject to large-scale land-use change and/or major improvement schemes often exhibit different trends to more 'natural' rivers. For example, on the Thames, the post-1940 decline in the frequency and extreme floods, which is not evident in Scotland or England, was attributed to channel dredging and flood alleviation schemes.

2.3. CLIMATIC CONTROLS OF FLOODING

2.3.1. Introduction

The relationships between climate and flooding are becoming increasingly important over a range of timescales. On the Mississippi river USA, Knox (1993) found that even, 'modest climatic changes, generally smaller than climatic changes predicted by global circulation models for greenhouse gas increases, caused large and sometimes abrupt adjustments in both magnitudes and frequencies of floods' (Knox, 1993, p432) , having far reaching implications for water engineers and geomorphologists alike. Over both historic and Holocene timescales in the United States (e.g. Knox, 1984; 1993, Knox *et al.*, 1975) and Australia (e.g. Erskine and Bell, 1982) workers have investigated high frequency short term (20-30 years) climatic changes and the response of river systems. In the UK investigations of this type have traditionally focused on the role of rainfall in flood generation (e.g. Howe *et al.*, 1967). More recent research has moved towards the analysis of the synoptic conditions and large-scale atmospheric circulations which dictate rainfall patterns (e.g. Grew, 1996; Grew and Werritty, 1995; Higgs, 1987c; Rumsby, 1991; Rumsby and Macklin, 1994, Longfield and Macklin, in press).

2.3.2. Controls of regional climate in the UK

Regional weather characteristics in the mid-latitudes, such as location of fronts, origin of airmasses and the position of storm tracks are controlled by the configuration of the circumpolar vortex in the upper atmosphere (Hirschboeck, 1987). This is a circumpolar flow of winds from west to east around the Earth over both hemispheres, caused by differential heating of the Earth`s surface, and rotation of the globe (Lamb, 1982). Imbalance within the flow causes pressure gradients, and the formation of high and low pressure systems, or anticyclonic and cyclonic synoptic systems. Atmospheric circulations, which steer synoptic systems, ultimately dictate the character of UK weather, and it is analysis of circulation types that can most effectively define and explain climatic variability (Kelly *et al.*, 1997)

In order to assess the variability of atmospheric circulation, a classification scheme is required. The main aim of such schemes is to 'identify a small number of patterns which occur most frequently, thereby describing much of the total variation in circulations with a relatively small number of patterns' (El-Kadi & Smithson, 1992, p432).

2.3.2.1. The Lamb (1972) catalogue of atmospheric circulation types

Classification of large-scale atmospheric circulations was pioneered in Europe by Franz Baur (cited in Kelly *et al.*, 1997), who developed the European Grosswetterlargen classification (see Yarnal, 1994 for summary). However, by far the most frequently used classification for the British Isles is that developed by Lamb (1972), which is based on the general steering and character of weather patterns over the UK (Jones and Kelly, 1982).

Table 2.1 : Weather associated with Lamb circulation types over the British Isles

Circulation Type	**Weather Characteristics**
Anticyclonic	• Mainly dry with light winds • Some summer thunder • Warm in summer and cold or very cold in winter
Cyclonic	• Depressions stagnating or passing over UK • Wet or disturbed weather • Variable wind direction and strength
Westerly	• Unsettled or changeable weather - most rain in N and W of UK • Mild and stormy in winter • Cool and cloudy in summer
North-westerly	• Cool with changeable conditions - particularly in N and E
Northerly	• Cold, disturbed weather in all seasons • Snow and sleet showers in winter - particularly in N and E
Easterly	• Cold in autumn, winter and spring • Occasionally severe weather in south, with snow • Snow or sleet showers in E and NE
Southerly	• Warm and thundery in spring and summer • Mild or cold in winter depending on airmass origin
South-westerly	• Very high rainfall totals over whole country • Warm moist airmass

Based on Lamb (1972) and Barry and Chorley (1982)

Lamb (1972) has classified British Isles weather types on a daily basis since 1861, based on the location of fronts and pressure systems, and direction of movement. Circulations are classified over the area 50° to 60° N and 10°W to 2°E. and represent one of the World's longest set of continuous daily weather charts (Kington, 1975; 1980) Seven primary weather types were recognised over the British Isles each with distinctive weather characteristics (table 2.1), five directional types (W, NW, N, E, and S) and two synoptic system types (cyclonic and anticyclonic). Lamb further recognised cyclonic and anticyclonic hybrids of the directional types, and an unclassified non-directional category, thereby totalling 27 individual circulation types. This subjective classification scheme is derived from surface synoptic charts and charts at the 500 hPa level (approximately 5.5km altitude in the UK (Davies *et al.*, 1997)) which describe flows higher in the atmosphere (Kelly *et al.*, 1997)

Advantages and limitations of the Lamb (1972) catalogue

Detailed reviews of the limitations of the Lamb catalogue are given by El-kadi and Smithson (1992) and O'Hare and Sweeney (1993), who state that problems primarily arise due to the fact that British Isles airflows are both complex and constantly changing, and to simplify this into a practical system of classification is extremely difficult Eight major limitations have been identified with respect to the Lamb classification :

1) Additional Classes : It is difficult to classify the sheer variety of UK weather into seven primary types, and the addition of the hybrid classes has further complicated the situation.
2) Unclassified Type : Complex airflows have to be included in the unclassified category.
3) Regional Variation : Marked differences in weather conditions can occur in different parts of the British Isles on the same day. This could be a result of there being several airflow types over the British Isles at any one time. Mayes (1991) has suggested a regional breakdown of circulation types would help redress the problem.
4) Lack of Objectivity : This is a very subjective system which is classified by the visual examination of data.
5) Synchronisation : Airflow type and associated weather may be difficult to correlate due to recording taking place at different times.
6) 'Within-type' variations : Relationships between Lamb types and precipitation may vary over long periods of time.
7) Distant origin : It is important to identify the origin of an airflow before it reaches the British Isles as weather characteristics can depend on this.

8) Meso-scale and micro-scale processes The Lamb classification is at the synoptic scale and gives information about the 'big picture' rather than giving precise information about fronts (meso-scale) or, for example, dewpoint temperature (micro-scale)

Despite these limitations the Lamb catalogue is a valuable source of long-term climatic data, indeed one of the chief advantages of the catalogue is its length and simplicity, combined with the fact that each individual circulation type can be related to characteristic weather conditions (O'Hare and Sweeney, 1993).

2.3.2.2. Circulation types : relationships with precipitation and recent trends

The first investigation attempting to relate precipitation to atmospheric circulation types was carried out by Murray and Lewis (1966). Using an early version of the Lamb catalogue they developed the PCSM indices to simplify information about synoptic features of the weather over the British Isles. The P-index provided a measure of progression or westerliness, the C-index cyclonicity, the S-index southerliness and the M-index meridionality. It was found that rainfall was closely correlated with a positive C-index (high frequency of cyclonic days), and to a lesser extent, with a positive P-index (high frequency of westerly days), a finding reiterated in later studies (e.g. Murray and Benwell, 1970; Perry, 1968; 1969). However, these indices imply a mutually exclusive relationship between circulation types (Grew, 1996) (e.g. C-index is positive when the number of cyclonic days is high, and low when the number of anticyclonic days is high), which in fact is far more complex. By applying Principal Component Analysis (PCA) to the Lamb catalogue Jones and Kelly (1982) also, in effect, derived four synthetic indices to describe variations in circulation types. The main advantage of this approach being that the indices 'are statistically uncorrelated and that a maximum amount of variance is accounted for in a minimum number of indices' (Jones and Kelly, 1982, p149). It was found that the first two components were significantly correlated with the England Wales precipitation (EWP) record, suggesting that enhanced anticyclonicity and/or decreased westerliness was associated with low rainfall, and enhanced cyclonicity and/or decreased anticyclonicity and westerliness were associated with high rainfall totals.

Although these studies suggest simple relationships between synoptic indices and precipitation they do not consider actual precipitation totals associated with individual Lamb types. Stone (1983a; 1983b) calculated mean daily precipitation for all 27 Lamb types over a 15-year period for central, eastern and southern England, and discovered that westerly, cyclonic and cyclonic-westerly circulations were three of the most frequently occurring types with high precipitation totals. A more comprehensive study of daily precipitation and Lamb types was undertaken by

Sweeney and O'Hare (1992) who mapped the geographical distribution of the mean daily precipitation associated with each Lamb type based on rainfall data at 65 lowland stations in the British Isles dating as far back as 1875. Cyclonic-south-westerly type was found to deliver the highest mean daily rainfall totals over the whole area (see figure 2.1), followed by cyclonic-southerly and south-westerly circulations. Anticyclonic-northerly and north-easterly types were found to be two of the driest circulations. Furthermore, of the three most frequent types, westerly, anticyclonic and cyclonic respectively, the cyclonic type was found to have the highest daily mean precipitation (4.2mm), followed by westerly (3.6mm) and anticyclonic (0.8mm). Marked geographical variations in rainfall receipt were also evident within individual circulations (see figure 2.2). Whilst cyclonic type showed a fairly uniform distribution of precipitation over the UK, westerly circulations were characterised by a marked west-east gradient in rainfall receipt, with areas to the east of major upland regions being drier, particularly on the east coast of Ireland and to the east of the Pennines.

Investigations concerning inter-annual and inter-seasonal variability within Lamb types has revealed a number of significant trends. The number of westerly days has declined markedly since the 1950s (Jones and Kelly, 1982; Lamb, 1972; Sweeney and O'Hare, 1992), a trend most pronounced in winter months, though evident in all seasons (Briffa *et al.*, 1990). The frequency of cyclonic-westerly circulations has also experienced a similar decline. Cyclonic and anticyclonic circulations have shown a corresponding increase, especially in the 1980s. Furthermore, south-westerly circulations have increased dramatically since the 1960s, with a two fold increase in frequency (Murray, 1993; Sweeney and O'Hare, 1992)

Figure 2.1 *: Mean daily precipitation for Lamb circulation types in the British Isles.*

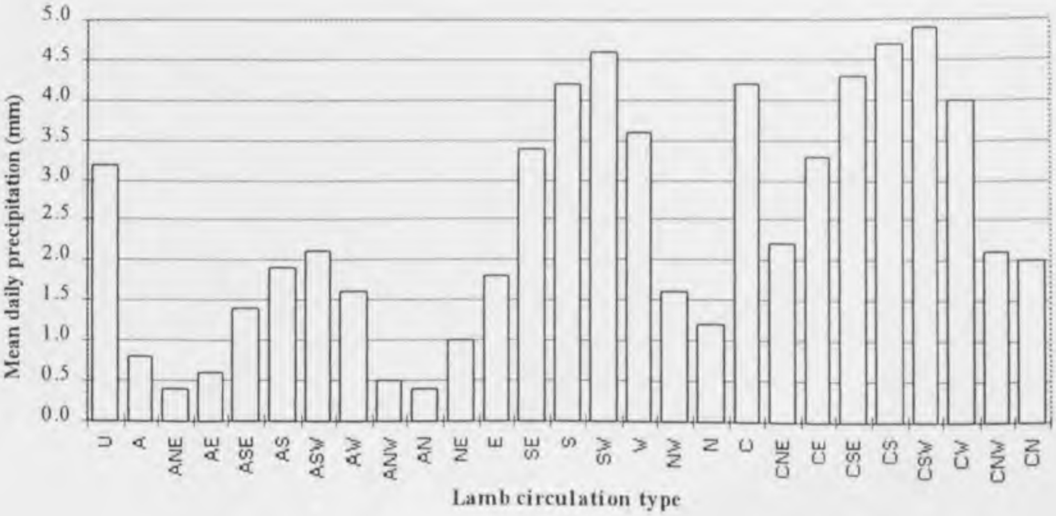
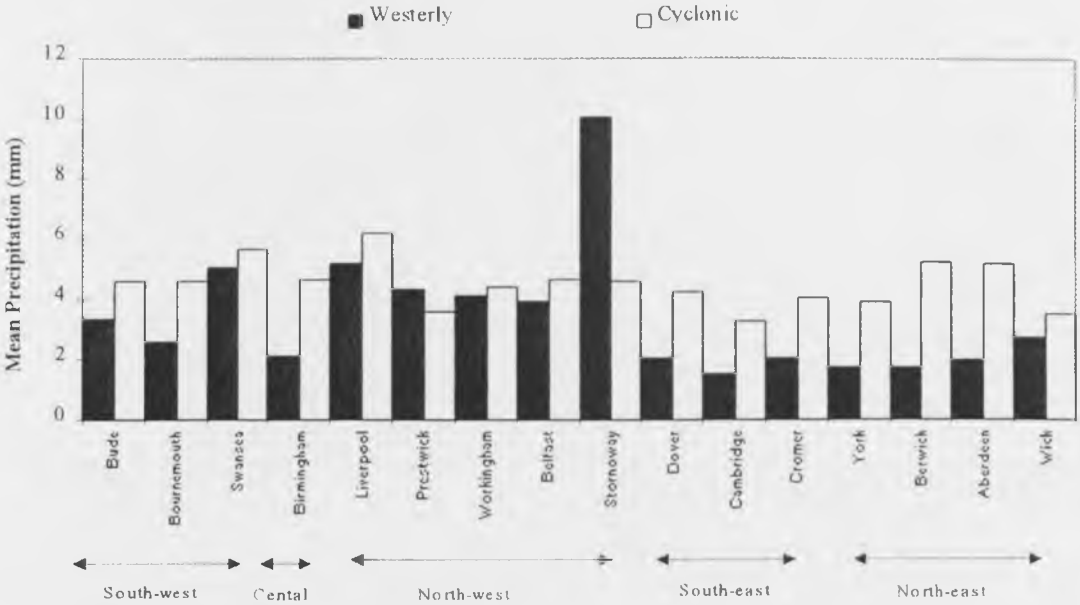


Figure 2.2 : *Mean daily precipitation for **westerly** and **cyclonic** Lamb circulation types at selected sites in the British Isles (after Sweeney and O'Hare, 1992)*



2.3.3. Atmospheric circulations and flooding

In the northern hemisphere the intensity, duration, spatial distribution and type of precipitation (i.e. rain or snow) is determined by the configuration of circumpolar upper air waves (the circumpolar vortex) (Charney and DeVore, 1979; Hirschboeck, 1988; Lamb, 1977; 1982). Large-scale upper air waves in the circumpolar vortex alternate between zonal (west to east) and meridional (north/south) forms. The strength, pattern and position of the circumpolar vortex is itself controlled by the equator to pole temperature gradient (Lamb, 1972). Warmer conditions produce a low temperature gradient resulting in a northward displacement of the circumpolar vortex and strongly zonal flow characterised by low amplitude widely spaced waves (Lamb, 1977, 1982). Cooler conditions cause the circumpolar air mass to be shifted southwards due to a steeper temperature gradient, resulting in a more meridional flow regime, with high amplitude waves and an increased number of meanders in the circumpolar vortex (Lamb, 1977; 1982).

The relationships between upper atmospheric configurations and flooding were first investigated by Knox *et al.* (1975) for the upper Mississippi valley, USA. These authors examined monthly frequencies of atmospheric circulation patterns which had been classified into 41 different types, or 'elementary circulation mechanisms' for the Northern Hemisphere between 1899 and 1969 by Dzerdzeerskii (1971). This number was reduced to 9 types relating specifically to North America by Knox *et al.* (1975) and variations within these types were linked to flood frequency and magnitude. This work was updated by Knox (1984) who divided a 115-year partial duration series of floods into 4 sub-periods on the basis of enhanced zonal or meridional circulation patterns. Meridional circulation was prevalent before 1895 and after

1950 and these periods coincided with higher flood magnitudes The intervening periods were dominated by a more zonal circulation patterns characterised by moderate flood magnitudes. A similar exercise was carried out by Higgs (1987c) on the River Severn at Bewdley with a 101-year record of daily mean flows, however the results showed significant differences to the work of Knox (1984). Periods with a zonal circulation regime were responsible for the highest flood magnitudes, Higgs attributed this difference to two main factors. Firstly, it would be unlikely for the same flood producing mechanism to occur in both the mid-west USA and Severn catchment, and secondly, anthropogenic land-use change in the form of increased river regulation, afforestation, land drainage and pasture improvement have significantly impacted on the flood regime of the River Severn

In a more recent study, Rumsby and Macklin (1994) investigated changes in flood frequency and magnitude and the vertical channel response on the River Tyne, and found a relationship similar to that of Knox (1984). Rumsby and Macklin (1994) used annual frequencies of Lamb (1972) weather types to calculate periods of enhanced meridional and zonal circulations An intermediate category was also identified when zonal and meridional frequencies were close to the long-term mean. Additional breakpoints to those identified by Knox (1984) were established and relationships with flood frequency and magnitude were investigated Major floods (>20 year return period) were associated with enhanced meridional circulation, whereas more moderate (5-20 year return period) flood events were characteristic of zonal periods. Intermediate periods were characterised by low flood frequency and magnitude.

These results raised the question as to why extreme flood events are more common when associated with meridional configurations of the circumpolar vortex. According to Rumsby and Macklin (1994) there are two synoptic characteristics which explain the relationship : (1) The high amplitude waves of meridional configurations can often be associated with stationary blocking situations which can lead to multiple peak, high intensity rainfall events (Rodda, 1970; Hirschboeck, 1987). (2) Lower winter temperatures result in an increase in the frequency of incursions by polar air masses, resulting in greater snow receipts, higher soil wetness and low evapotranspiration rates combining to cause a large flood peak through increase runoff rates.

The importance of geographical location in determining the magnitude of floods generated by meridional and zonal types can be illustrated by comparing the Tyne and Severn basins. The Tyne basin is located to the east of the Pennines, and is in the rain-shadow of westerly or zonal weather systems (Rumsby and Macklin, 1996). This area is more susceptible to meridional weather systems from the north and north-east which have gathered moisture from passage over the North Sea. Whereas the Severn basin is located on the west of the British Isles and consequently rainfall receipts are higher from zonal weather systems.

In all the studies considered thus far, relationships between flooding and atmospheric circulation types have been established using monthly or annual groupings of circulation types (e.g. zonal). Although this will give an indication of the general character of climate over an extended period, it gives no indication of those synoptic situations that directly cause flood events. A recent study by Grew (1996) has addressed this problem. Grew classified each individual flood event from over 130 Scottish POT records according to the circulation or weather type that 'triggered' the event. The Mayes (1991) regional airflow classification was used to determine the weather type on the day of flood and the preceding day. Once each flood had been classified, a primary (most common flood trigger) and secondary weather type was established for each site. It was found that three circulation types commonly trigger flood events in Scotland, cyclonic, westerly and south-westerly. The relative importance of these types is heavily dependent upon geographical area. Floods in the western half of Scotland are more commonly triggered by westerly and south-westerly weather types, whereas floods in eastern Scotland are more often caused by cyclonic weather types. This relationship simply reflects the geographical variations in rainfall receipt which occur between weather types. Both westerly and south-westerly types have a marked west-east rainfall gradient and supply higher precipitation totals to the west of Scotland. In the east of Scotland it was suggested that cyclonic systems which are often associated with easterly rain-bearing winds from the North Sea have a greater influence on flood generation in this area.

Once primary flood trigger types had been identified for each site Grew attempted to link observed temporal variations in flood frequency and magnitude records to variations in the frequencies of important flood trigger types. Despite concluding that 'a straightforward relationship between the pattern of flood frequencies and trigger weather types and/or flood seasonality does not exist' (Grew, 1996, p174), some relationships were evident. In western Scotland a decline in flood frequency between the late-1960s and early-1970s was associated with a decline in the winter (December-February) frequency of westerly and south-westerly weather types. In contrast, an increase in flood frequency after the early-1970s coincided with a rise in the winter frequency of westerly and cyclonic weather types. In eastern Scotland, declining flood frequency in the early-1970s was also associated with a decline in cyclonic frequencies in winter and autumn (September-November). It proved much more difficult to establish links between flood magnitude and weather types, and it was concluded that 'the relationship between mean exceedances and weather types is one which cannot be readily explained by this research' (Grew, 1996. p180)

2.4. LAND-USE CHANGE AND FLOODING

2.4.1. Introduction

Changes in land-use are often cited as contributory factors to variations in flood frequency and magnitude. It has been suggested that land drainage schemes (e.g. Caufield. 1982; Howe *et al.*, 1967; Oldfield. 1982) and even increases in livestock numbers (e.g. Sansom. 1996) can contribute to increased flooding Similarly, land-use changes such as river channelization (e.g Brookes, 1985) and the construction of reservoirs (Higgs and Petts. 1988) have been shown to decrease flood magnitude, at least at a local level Thus. the main aim of this section is to consider the effects that various changes in land-use may have on flood frequency and magnitude. The main areas considered are, changes in agricultural land-use and practices. land drainage, river channelization and reservoir construction

2.4.2. Agricultural practice and land-use change

Over the past two decades there has been a great deal of research on the effects of soil erosion on agricultural land. This work was prompted by a rise in the number of cases when severe erosion was reported in the 1970s and 1980s (Boardman, 1990; Boardman and Favis-Mortlock, 1993). Any large-scale change in agricultural practices or land-use that alter rates of runoff from agricultural land may affect flood frequency, and, in particular, flood magnitude through alterations in the timing of flood peaks. Evans (1990) suggests a number of factors which control water erosion on agricultural land, including gradient, vegetation cover, soil surface roughness, rainfall intensity, the morphology of eroding fields, soil type, crop type and cultivation methods. Not all of these factors are important in terms of runoff reaching arterial river channels, however, the two most important are likely to be surface roughness (which affects infiltration rates) and cultivation techniques

In order to store and absorb rainfall the surface of soil needs to be rough (Evans, 1990). Rougher soil surfaces are associated with ploughing when compared to cultivation by tines or discs. The smoothest soil surfaces occur after seedbed preparation by harrowing, and then drilling (Evans, 1980, 1996). Smoother soil surfaces promote runoff due to a reduction in infiltration capacity, therefore it may be suggested that ploughing could reduce runoff when compared to unploughed land. Furthermore, topsoil can become compacted by heavy farm machinery, resulting in low soil porosity and permeability, and the resultant wheelings or 'tramlines' can become particularly compacted by frequent use when applying fertiliser and pesticides for example (Evans, 1996), increasing the potential for rapid runoff

Allied to the perceived increase in soil erosion in the 1970s and 1980s were reports of a rise in the incidence of flooding caused by runoff from agricultural land in several areas of north-western Europe (Boardman *et al.*, 1994). The affected areas were typically hilly with easily erodible silty loessial soils, which caused damage to nearby properties through the generation of sediment laden 'muddy floods'. In Britain two main factors have been cited as causing increased soil erosion and runoff on agricultural land; the intensification of farming, and a significant change in land-use (Boardman and Favis-Mortlock, 1993). Intensification of farming has resulted in larger fields with the removal of field boundaries such as hedgerows, the use of heavier farm machinery and a shift to monoculture. However, Boardman and Favis-Mortlock (1993) suggest that the most important factor in terms of increased erosion and runoff has been a significant land-use change. This can be clearly illustrated in the South Downs of south-east England, an area which has been subject to intensive study (e.g. Boardman, 1990; 1995; Boardman *et al.*, 1994). Serious damage to property in this area as a result of rapid runoff from ephemeral gullies was first recorded in 1976, and then again in 1982, 1987, 1991 and 1993. All of these events occurred in autumn and early winter months (Boardman, 1995). It was found that the onset of the flooding and erosion problem coincided with a change in the crop type being grown in the area. Since the mid-1970s the dominant crops were autumn-sown 'winter' cereals, as opposed to the more traditional spring-sown cereals, since higher yields were obtained under a winter sowing regime (Boardman, 1995). The increased flood risk was caused by inadequate crop cover of arable soils, by crops such as winter wheat during the wettest months of the year (October-March), resulting in enhanced runoff and erosion. Under a traditional spring-sowing regime the soil would not have been bare in the winter months. Furthermore, soils are also exposed for longer periods since autumn-sown crops tend to develop more slowly than spring-sown crops (Frost *et al.*, 1990). With respect to England and Wales as a whole, the area under winter cereals increased almost threefold between 1969 and 1983 (Evans and Cook, 1986). Boardman *et al.* (1994) have also suggested five other farm management techniques that may increase the risk of runoff generation, in conjunction with the shift to larger fields and erosion susceptible crops.

(1) The preparation of fine seedbeds : the risk of aggregate breakdown by rainfall increases.

(2) Reduction in organic matter content of the soil through a lack of grass in crop rotations, and a reliance on chemical fertilisers.

(3) The rolling of fields after seed drilling : produces a compact surface with a low micro-topography

(4) Vehicle wheel tracks : severe compacting can result in wheelings acting as channels.

(5) Direction of ploughing : fields are commonly ploughed in downslope direction which may promote runoff generation.

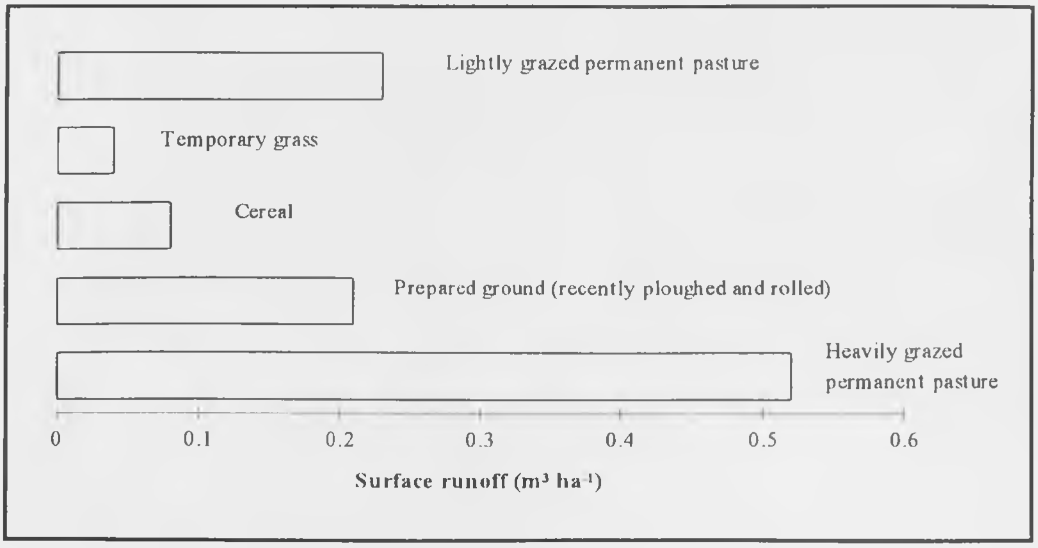
Finally, a study by Heathwaite *et al.* (1990) examined the impact of large-scale conversion of grassland to arable land (a common feature in recent agricultural history), and associated increase in livestock numbers on remaining grassland, on surface runoff and sediment production in south-west England These authors investigated claims that agricultural intensification such as this may accelerate soil erosion due to, (1) reduced soil organic matter levels in arable areas (organic matter is important for 'soil particle cohesion' and 'the maintenance of soil structural stability'), and (2) that increasing livestock numbers may accelerate erosion due to surface soil compacting, and the stripping of vegetation cover as a result of intense grazing. The effects of ploughing operations were also considered. Field measurements and hillslope plot experiments were carried out on five small (0.9-23.6 km^2) catchments around Slapton, south of Dartmoor, each with a distinctive land-use type. Measurements showed that infiltration capacity of the soil increased following ploughing, whereas grazing cattle reduced infiltration capacity. Furthermore, experimental plot studies with simulated rainfall of 12.5 mm hr^{-1} for a period of four hours were undertaken to examine the effects of different land-use types on infiltration capacity, runoff and soil bulk density (see table 2.2).

***Table 2.2** : The effect of different land-use types on surface runoff from hillslopes (after Heathwaite et al., 1990)*

Land use	**Rainfall intensity (mm h^{-1})**	**Total runoff (mm)**	**Percentage runoff as rainfall**	**Infiltration capacity (mm h^{-1})**	**Bulk density (g cm^{-3})**
Temporary grass	12.50	2.3	5	12.33	0.96
Cereal	12.50	3.7	7	11.04	1.08
Bare ground	12.50	10.6	21	4.00	0.93
Lightly grazed permanent pasture	12.50	11.6	23	5.85	1.12
Heavily grazed permanent pasture	12.50	26.5	53	0.10	1.18
Heavily grazed permanent pasture	3.25	2.6	5	0.10	1.18

The highest runoff volumes were recorded for heavily grazed permanent pasture (53% of total rainfall input), with high soil compaction rates reflected in the low infiltration capacity (0.10 mm hr^{-1}) and high soil bulk density (1.18 g cm^{-3}). Runoff was also high from bare ground (21% of total rainfall input) even though the land had recently been ploughed and rolled. Lowest runoff volumes were recorded on ungrazed land (i.e. temporary grassland and cereals) where high infiltration capacities and low bulk densities resulted in only 5 to 7% of rainfall being converted to runoff. On the basis of these rainfall-simulation results Heathwaite *et al.* (1990) also examined the effects of land-use on predicted surface runoff in m^3 ha^{-1} (see figure 2.3). Similar trends to those outlined above were evident and two main conclusions were drawn. First, the 'surface runoff in the absence of vegetation cover is up to ten times greater than land with intact crop cover (temporary grass and cereals)', and second that 'the magnitude of runoff increases if grazing animals are present.' (Heathwaite *et al.*, 1990, p80).

***Figure 2.3** : The effect of land-use on predicted surface runoff (m^3ha^{-1}) (after Heathwaite et al., 1990)*



2.4.3. Agricultural land drainage

Hill (1976) suggests that 'agricultural land drainage may be defined as the removal and disposal of excess water from the soil in order to increase its agricultural capability' (Hill, 1976, p252). The main benefits of drainage schemes are to increase crop yields and improve crop and soil management (Massey, 1973; Trafford, 1972). However, whilst the benefits for crop production are widely accepted, the effects of drainage schemes on downstream river flows has long been a controversial issue (see Bailey Denton, 1862). In a review of the impacts of improved land drainage on river flows in the UK, Robinson (1990) identified five main effects of artificial land drainage :

1. The effects of an increased drainage density
2. The effects of an enlarged available soil water storage capacity
3. The effects of storm characteristics and antecedent conditions
4. The effects of different types of drainage
5. The effects of drainage extent and location within a catchment

The remainder of this section examines the type of drainage schemes utilised in the UK and considers in detail the findings of Robinson (1990), which represents the most comprehensive study into the downstream effects of land drainage schemes over a range of spatial scales.

2.4.3.1. Types of drainage system used in the UK

In-field drainage in the UK typically consists of a system of sub-surface pipes, termed 'underdrainage'. However, in more marginal moorland areas, usually in upland Britain, the cost of underdrainage is considered too expensive and open ditches are used to drain the land. Robinson (1990) reviews both techniques and suggests that there are two main situations where drainage is required. Firstly when surface soil layers are saturated due to low soil permeability (e.g. clay soils), or a perched water table, which does not allow the free-drainage of surface water, and secondly when groundwater levels are high (usually associated with permeable soils). The layout of sub-surface drainage systems depends on soil type and the drainage problem being tackled. In heavy clay soils drains are usually closely spaced (5-15m), whereas drains associated with groundwater problems are more widely spaced (upto 40m). Furthermore, the required drain spacing in clay soils is often so small that the high density of pipe systems required would be too expensive, consequently more economical secondary treatments are utilised that aid the movement of water to a less dense pipe system. The two main methods of secondary drainage are subsoiling and moling, carried out at spacings of 1 to 2 metres. Subsoiling introduces an artificial drainage structure into the soil by shattering and lifting of severely compacted subsoil layers through deep ploughing. In more plastic clayey soils a mole plough in the form of a bullet shaped metal rod is used to create a 'mole channel' and fissuring of upper soil layers (Robinson, 1990)

In moorland areas the most widely used form of drainage is the cutting of open ditches, commonly referred to as 'moorland gripping'. The main aim of this type of drainage is to improve the cover of heather in moorland areas and therefore increase livestock and grouse numbers, although the success of this technique has been questioned (Stewart and Lance, 1983) Ditches are cut using a 'Cuthbertson' drainage plough at spacings of around 20m, and are approximately 40-45cm deep (Robinson, 1990).

2.4.3.2. The effects of land drainage on floods

Robinson's (1990) review of literature relating to land drainage revealed two 'schools of thought' with respect to the effects on peak river flows. The first suggested that land drainage reduces downstream flooding, by increasing the capacity of the soil to absorb rainfall, and increasing travel times as a consequence of deeper flow pathways. The second suggested that land drainage increases downstream flooding through more rapid removal of water from soils Robinson argued that this was a 'major over-simplification' of the complex processes involved, based on the results of field-scale (ranging from 0.005 - 13.5 ha) and catchment-scale (around 17 km^2) studies.

At the field-scale, soil type was found to be one of the most important factors controlling runoff response to drainage. It was found that 'at wetter sites (high rainfall and/or high clay content) peak flows are reduced, whilst at drier sites (lower rain, more permeable soils) peaks are increased' (Robinson, 1990, p187.), a finding which contradicted earlier studies (e.g. Bailey and Bree, 1981; Rycroft and Massey, 1975; Trafford, 1973). However Robinson confirmed earlier findings that the type of drainage system installed is also a major factor. Higher peak flows were evident at sites where secondary treatments had been applied, when compared to those with pipe drains alone (Armstrong and Garwood, 1991; Trafford and Rycroft, 1973). Similarly, higher peaks were associated with open ditch drainage systems when compared to subsurface drainage schemes (Paivanen, 1976). Furthermore, when assessing the effects of drainage it is important to consider the age of the drains installed as they become less effective with age. Typically pipe drains remain effective for around 50 years, whereas secondary treatments such as moling and subsoiling are only effective for around 5 years, and therefore require more frequent renewal.

At the catchment-scale Robinson found that the impacts of drainage may differ from those observed at the field-scale, primarily due to the effects of improvements to ditches and arterial channels, and the effects of routing of flows from different parts of the catchment. Improvements to ditches tends to speed flows, similarly improvements to the arterial channel, which often accompany land drainage schemes. tend to increase peak flows through reduction of overbank storage and increased channel velocities.

When assessing the impact of drainage in river catchments one must also consider the extent and location of drainage schemes Clearly, schemes which cover only a small proportion of a catchment are unlikely to have a major impact on peak flows Similarly, the effects of drainage schemes on larger catchments may be difficult to discern given the large number of varying characteristics over the basin (Robinson, 1990). However. the location of drainage schemes within a catchment will also influence the effect of peak discharge (Acreman. 1985b; Newson and Robinson, 1983; Robinson. 1990). For example. 'due to the lagging and routing of subcatchment flows to the outlet, increases in peaks at one point in a channel network may result in decreases at other points in the system' (Robinson, 1990, p 201) Furthermore, the synchronisation of flood peaks from different parts of the catchment is of crucial importance (Whitely, 1975; 1979). Any drainage schemes in the lower parts of a catchment that slow runoff into the main arterial channel may increase flood peaks, whereas schemes that speed runoff may reduce the flood peak, conversely, the effects may be the opposite in the upper reaches (Wisler and Brater, 1959).

With respect to upland drainage, most studies have been concerned with the effects of ‘moorland gripping’ and pre-afforestation drainage schemes. This type of drainage usually takes the form of open ditches cut into poorly drained peat moorland. Increases in peak flows and flood frequency prior to forest canopy closure have been noted (Hyvarinen and Vehvilainen, 1981), principally due to increased drainage density (Robinson, 1979; 1981; 1986). With respect to moorland gripping, drainage of blanket peat in the northern Pennines resulted in reduced time to concentration and increased peak flood discharge, in effect a more ‘flashy’ response as a result of increased speed of runoff (Conway and Millar, 1960; Robinson, 1985). However, several studies have suggested that upland drainage has reduced downstream flood peaks (e.g. Burke (1975) working in the west of Ireland) though these differences were attributed to variations in soil type, drainage type, ploughing pattern and climatic characteristics (McDonald, 1973a; 1973b; Robinson 1985).

In summary, the effects of drainage schemes on downstream flood peaks depends on a large number of factors, such as soil type, climate, and the type, extent and location of drainage schemes within a catchment. The majority of studies have been undertaken at relatively small scales (catchments no larger than $20km^2$) and attempting to assess the effects of drainage in larger basins is therefore difficult. Indeed Higgs (1987a) suggests that 'there are thus inherent dangers in extrapolating research results from one catchment study to others.' (Higgs, 1987a, p56).

2.4.4. River channelization : methods and hydrological consequences

'River channelization in England and Wales has been undertaken for the purpose of reduction or alleviation of flooding, drainage of agricultural land, benefit of navigation, or reduction or prevention of erosion.' (Brookes *et al.*, 1983, p105). These channel improvement schemes occur in both urban and rural areas, and the main methods of channelization have been summarised by Brookes (1985) as follows :

- **Resectioning :** the deepening and widening of river channels to increase capacity and contain flood water within the channel.
- **Realignment :** where river channels are shortened by artificial cutoffs.
- **Diversions :** where flood flows are diverted around areas that need to be protected (e.g. in urban areas where channel widening is not practical).
- **Embankments :** designed to contain high flows by artificially increasing channel capacity.
- **Bank protection :** protection against bank erosion.
- **Lined channels :** channels are lined with concrete to speed flow velocities and prevent erosion. Usually constructed in major urban areas (e.g. London and Los Angeles).
- Other channelization schemes include the construction of **culverts** and **channel maintenance**, such as the removal of obstructions and dredging. Channelization does not include completely artificial watercourses such as open ditches and pipes installed for drainage of agricultural land (Brookes, 1985).

The majority of research concerned with the environmental consequences of river channelization has been conducted in the USA. Brookes *et al.* (1983) review both North American and European research and suggest that most studies have been concerned with the morphological (e.g. Daniels, 1960; Emerson, 1971, Parker and Andres, 1976) and ecological impacts (e.g. Bayless and Smith, 1967; Bouchard *et al.*, 1979; Hansen, 1971; Muller, 1953; Schmal and Sanders, 1978) of channelization. However, there have been a number of studies that have attempted to investigate the hydrological consequences of river channelization. The

Table 2.3 : Hydrological consequences of river channelization (from Brookes, 1985)

Area applied	**Type of channelization**	**Evidence**	**Effects**	**Source**
Britain	Channel improvement works	Inferred	Downstream flooding evaluated at both the basin and individual stream levels	Heneage (1951)
River Tame, UK	Channel improvement works (including resectioning)	Inferred	Changes in the basin upstream have not changed flood flows in the lower river	Wood (1981)
River Trent, UK	Realignment	Theoretical	Cutoff would relieve local floods but increase the flood discharge peak	Binine (1936)
Colombo, Ceylon	Embankment	Analysis of Hydrographs	Elimination of storage capacity of floodplain will increase floods over unprotected areas	Hilman (1936)
Blackwater River, Missouri, USA	Realignment	Eye-witness accounts	Flooding downstream from straightened reach	Emerson (1971)
Sangamon River, Illinois; Fox, Wyconda and Salt Rivers, Missouri, USA	Realignments	Observation	Downstream flooding	Lane (1947)
Bayou, Cocodrie and N.Bayou, Cocodrie, Louisiana, USA	(unspecified)	Observation	Downstream flooding	Callison (1971)

findings of some of the most significant studies have been summarised by Brookes (1985) and are shown in table 2.3. Many of these authors suggest that channelization schemes have increased downstream flooding (Emerson, 1971; Hillman, 1936; Lane, 1947), principally due to the reduction in floodplain storage capacity and increases in flow velocities. Similarly, Heneage (1951) (cited in Brooks, 1985) reported that flood protection works of the River Trent (protecting an area of 1012ha) increased downstream flood levels by 10-13cm, although model tests suggested that the effect only persisted a few miles downstream. Furthermore, Engel (1985) (cited in Robinson, 1990) demonstrated that channel improvement on the River Rhine has resulted in increased peak flows and accelerated flood wave velocities. Engel estimated that a flood in December 1882 (before major channel improvement) with a recorded discharge of 4680 m^3s^{-1} at Maxau, would have exceed 6400 m^3s^{-1}, and peaked three days earlier under 1982 channel conditions (after major channel improvements). However, on the River Tame upstream channelization works did not appear to have altered downstream flood response (Wood, 1981). Indeed it has been suggested that 'it is an exaggeration to assume that channelization always causes downstream flooding' (Keller, 1980, p122).

In Britain channelization in the form of arterial channel improvements often precedes agricultural field drainage (Essery and Wilcock, 1990) for two main reasons (Robinson, 1990) :

1. To reduce water levels in the main channel in order to enable free-draining from outfalls of field drainage

2. To increase channel capacity and reduce overspill onto river floodplains

Robinson (1990) analysed flow data before and after arterial drainage works for four British catchments and concluded that local flooding was reduced, but increased flood peaks and shorter response times were evident downstream. These effects appeared to be greatest for large magnitude floods, since prior to arterial drainage these events were subject to large overbank storage volumes. It was also suggested that such schemes transfer the flooding problem further downstream.

At the basin scale it is probably alterations in the timing of flood peaks from tributaries that control the response of rivers to channelization. If channelization results in the de-synchronisation of flood peaks then downstream flood levels may be reduced, conversely if flood peaks are combined downstream flood levels may increase (Brookes, 1985). However, Keller (1980) has urged caution when attempting to interpret the effects of channelization and suggests that 'each stream must be evaluated independently if accurate predictions of downstream flooding are to be achieved. Generalizations remain dangerous' (Keller, 1980, p122).

2.4.5. The effects of reservoirs on flood flows

In a comprehensive review of hydrological changes as a consequence of river regulation Higgs and Petts (1988) suggest that 'any river impoundment will change the magnitude and frequency of flood flows at least to some degree' (Higgs and Petts, 1988, p353). The principal effects of reservoir construction on flood flows are concerned with the magnitude and timing of events. Flood magnitudes are reduced through the attenuating effects of increased storage capacity provided by the reservoir. Whereas the timing of flood peaks from reservoirs are often 'lagged' which can result in de-synchronisation of mainstream and tributary peaks (Petts, 1984; Petts and Lewin, 1979).

Reduction in the magnitude of the mean annual flood has been noted by several authors. Construction of the Clatworthy Reservoir (catchment area of 18.2 km^2) on the River Tone in Exmoor, resulted in a 60% reduction of the mean annual flood below the dam (Gregory and Park, 1974). Petts and Lewin (1979) have also reported reductions of the mean annual flood by 11% at Avon Reservoir, 14% at Stocks Reservoir on the River Hodder, and of 39% on Sutton Bingham Reservoir on the River Yeo, when comparing reservoir outflow and naturalised discharges. Furthermore, Gustard *et al.* (1986) calculated that for 29 regulated rivers in Britain, the mean annual flood was reduced on average by 26%, when compared to natural discharges.

The effects of reservoirs on flood peaks diminishes downstream as the proportion of uncontrolled catchment increases (Petts, 1984; Petts and Lewin, 1979). The effects of Clatworthy Reservoir were evident downstream until the area impounded was less than 10% of the total catchment area (Gregory and Park, 1974). On the upper Severn a decline in flood frequency and magnitude after 1968 was found to coincide with variations in seasonal rainfall. However Clywedog reservoir was constructed in this year and it was suggested that 'Clywedog Reservoir has probably accentuated this natural decline in floods at least for 40 km downstream' (Higgs and Petts, 1988, p 366).

With respect to flood magnitude Petts and Lewin (1979) used a Fortran Flood Routing Program to examine flood hydrographs in reservoired catchments. Table 2.4 shows the proportion of catchment impounded and estimated peak flow reduction immediately downstream of twelve British reservoired catchments. Peak flow was reduced between 9% and 73%, dependent on the proportion of catchment impounded. Generally, peak flow reductions are greatest for those catchments with the largest area impounded.

Table 2.4 : Regulation of flood discharges downstream of selected British reservoirs (after Petts and Lewin, 1979)

Reservoir / Area	**Proportion of catchment impounded (%)**	**Peak flow reduction (%)**
Avon, Dartmoor	1.38	16
Fernworthy, Dartmoor	2.80	28
Meldon, Dartmoor	1.30	9
Vyrnwy, mid-Wales	6.13	69
Sutton Bingham, Somerset	1.90	35
Blagdon, Mendips	6.84	51
Chew Manga, Mendips	8.33	73
Stocks, Forest of Bowland	3.70	70
Daer, S. Uplands	4.33	56
Camps, S. Uplands	3.13	41
Catcleugh, Cheviots	2.72	71
Ladybower, Peak District	1.60	42

Reservoirs often exhibit a seasonality of peak flow reduction, which is related to the operational rules of individual reservoirs. In summer demand for water supply is often high, which results in draw-down of the water level in the reservoir. This results in increased potential storage capacity, which is particularly important in areas where convective summer storms cause floods (Higgs and Petts, 1988; Petts, 1984; Petts and Lewin, 1979). In winter months reservoirs may be at or near spillweir capacity with little potential for flood storage, therefore having a lesser effect on the reduction of winter peak flows.

Analysis of annual flood frequency distributions pre and post-reservoir construction (table 2.5) indicate that reservoirs are most effective at reducing peak flows for small and moderate magnitude floods (lower pre and post-construction ratios). Whereas the regulation of rarer high magnitude events is less effective (Higgs and Petts, 1988; Petts and Lewin, 1979).

Table 2.5 : *The ratios of post to pre-dam discharges for flood magnitudes of selected frequency, and reduction in mean annual flood (after Petts and Lewin, 1979)*

River / Reservoir	**Recurrence Interval (years)**			
	1.5	**2.3**	**5.0**	**10.0**
River Avon, Avon Reservoir	0.90	0.89	0.93	1.02
River Hodder, Stocks Reservoir	0.83	0.86	0.84	0.95
River Yeo, Sutton Bingham Reservoir	0.52	0.61	0.69	0.79

Data are ratios of post to pre-dam discharges

In summary, reservoirs attenuate flood peaks due to storage of a portion of the flood flow and de-synchronisation of tributary and mainstream peaks The downstream impact depends upon the location of reservoirs, the frequency and order of the tributaries affected, the proportion of the catchment impounded and the operational rules of the reservoir Peak flow reduction tends to be greatest in summer months and for minor and moderate magnitude flood events

2.5. SUMMARY OF LITERATURE REVIEW

Temporal and spatial variations in flood frequency and magnitude have been identified in a large number of flood studies throughout the British Isles. These variations have been attributed to both climate and land-use changes, and combinations of the two In terms of climatic controls it appears that trends in precipitation and flooding have been linked to hemispheric-scale atmospheric circulation patterns in the USA and UK. Periods with enhanced meridional (north/south) circulations, occurring under generally cooler conditions, have been shown to be associated with high magnitude flood events in north-east England. Periods with enhanced zonal (west to east) circulation types, which tend to occur under warmer conditions, are associated with a higher frequency of more moderate flood events. At a more regional-scale, individual circulations types have been identified which ‘trigger’ floods in Scotland. Cyclonic, westerly and south-westerly circulations were found to be the most important flood generating types, and links have been suggested between the annual and seasonal frequencies of these circulations and variations in flood frequency

In terms of land-use controls, changes in agricultural practices such as the switch from spring to winter-cereals has been shown to increase the rate of runoff from agricultural land. Similarly the presence of grazing animals and intensification of farming have also been related to soil erosion and increased runoff. Alternatively, land drainage schemes can either increase or decrease peak flows into arterial channels depending on a large number of factors including, soil type, climate, and the type, extent and location of scheme installed. Channelization schemes have been shown to reduce local flooding, although only shifting the problem further downstream, and finally, reservoirs have been shown to reduce flood peaks, primarily through the storage of a portion of the flood flow. However, at the basin scale, assessing both the spatial and temporal dimensions of land-use impacts which may alter flood hydrology is of paramount importance. Although, the task to disentangle the relative roles of each land-use type at such a large spatial scale is undoubtedly complex. Indeed, Higgs (1987a) points out that 'in larger catchments the averaging effects of differing land uses will mask that of individual treatments' (Higgs, 1987a, p29), this problem being further complicated by climatic variation.

CHAPTER 3

BACKGROUND TO STUDY AREA : THE YORKSHIRE OUSE BASIN

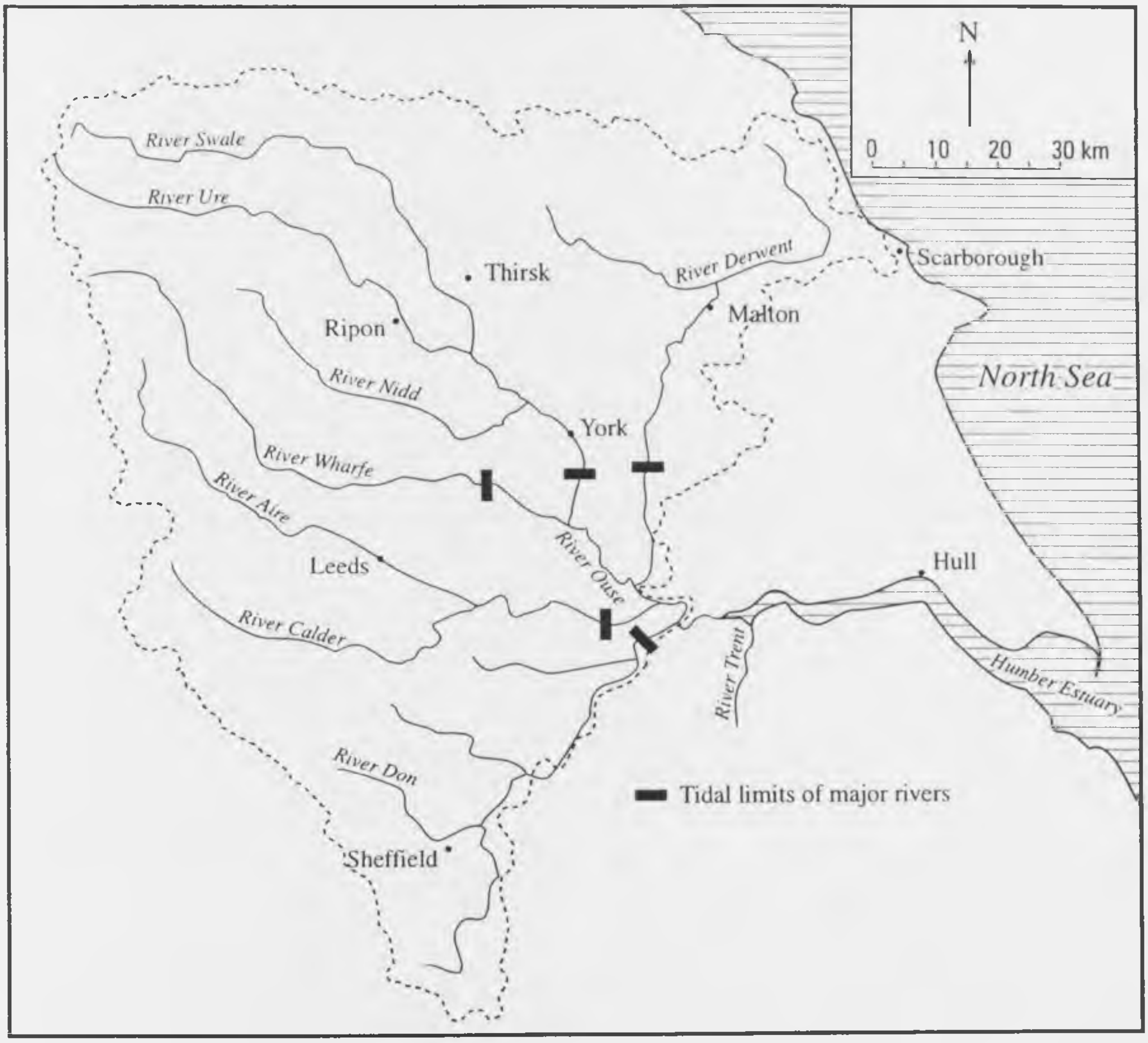
3.1. INTRODUCTION

The Yorkshire Ouse has eight major tributaries, the Swale, Ure, Nidd, Wharfe, Aire, Calder, Don and Derwent (see figure 3.1). Six of these rivers drain in a south-easterly direction from the Yorkshire Dales National Park area of the Pennines. Of the remaining two rivers, the Derwent drains in a southerly direction from the North Yorkshire Moors and the Don in a north-easterly direction from the northern part of the Peak District National Park. The tidal limits of all rivers are shown in figure 3.1; the Ouse becomes tidal downstream of Naburn Weir. At Skelton (SE 568 554) 6km upstream of York, the maximum recorded discharge is 622.0 m^3s^{-1} recorded in January 1982, and the mean annual flood is 302.0 m^3s^{-1}. The Yorkshire Ouse has a total catchment area in excess of 9000 km^2 at the confluence of the River Ouse and its most southerly tributary, the Don.

3.2. LATE QUATERNARY GLACIAL HISTORY

The present day drainage system in the Ouse basin developed after the termination of the Late Devensian glaciation (18000 - 13000 BP). During this period two ice masses encroached from the west, north and east (Kent *et al.*, 1980). To the west, a glacier from the Lake District breached the Pennines through Stainmore Gap and was split into two flows by the Cleveland Hills. The southerly tongue of ice was deflected south into the Vale of York. From the north-east, the North Sea ice sheet moved across Holderness and into the Humber Gap, blocking drainage from the Vale of York and the Trent and Ancholme valleys (Kent *et al.*, 1980). The Vale of Pickering was also blocked by ice, forming Lake Pickering which overflowed through Kirkham Gorge to form the present-day course of the Derwent. Blockage of the northern Vale of York and the Humber Gap also resulted in the formation of a large proglacial lake, Lake Humber, which covered much of the low lying Vale of York and overflowed through the Lincoln Gap (Catt, 1987; 1990). This lake initially reached a level of 33m AOD, which soon fell to between 10 and 14m AOD (Gaunt, 1974). Lake Humber had infilled by around 11000 BP. (Gaunt, 1981; Gaunt *et al.*, 1971), and following breaching of the glacial deposits blocking the Humber, river systems developed on the fine grained lake deposits. Low sea-level around

Figure 3.1: *Location of study area and tidal limits of major rivers*



this time (Gaunt and Tooley, 1974; Pethick, 1990) caused river channels to deeply incise until around 8500 BP (Gaunt *et al.*, 1971), when rising sea-level resulted in alluviation of valley floors.

3.3. BASIN GEOLOGY

The Ouse basin consists of four geologically distinct areas (fig 3.2), (1) the Yorkshire Dales in the north-west of the catchment which drain the upper Swale, Ure, Nidd, Wharfe, Aire and Calder are underlain by Carboniferous limestone and Millstone Grits. (2) The lower reaches of these rivers flow across the Permo-Trias magnesian limestone and mudstone Pennine piedmont. (3) The Vale of York in underlain by Permo-Trias Sherwood Sandstones, and has a thick covering of Quaternary glacial and alluvial deposits. (4) The Derwent catchment to the north-east of the Ouse Basin drain the North Yorkshire Moors which are underlain by Jurasic rocks, on the south-eastern margin of the Derwent there are outcrops of Cretaceous chalk, and the lower part of the system is dominated by Triassic mudstones and sandstones underling thick Quaternary deposits.

3.4. BASIN RELIEF

There are several distinct relief zones in the Yorkshire Ouse basin (fig 3.3) Firstly, the Pennines on the west of the catchment, encompassing the Yorkshire Dales National Park and the northern Peak District National Park, have peaks in excess of 700m AOD. The highest point in the catchment is Great Shunner Fell between the head of the Swale and Ure at 713m AOD. The majority of rivers flow in a south-easterly direction through the steep-sided Yorkshire Dales and into the Vale of York. Secondly, the Vale of York is an area of low lying land which runs north-south between the highlands of the Pennines and the North Yorkshire Moors to the southern edge of the basin, land to the south of York is predominantly less than 20m AOD. Thirdly, the north-east of the catchment is dominated by the North Yorkshire Moors with peaks in excess of 450m AOD.

3.5. BASIN CLIMATE

Annual rainfall totals vary markedly over the Ouse basin and are strongly related to altitude. Figure 3.4 shows average annual rainfall isohyets over the basin between 1941 and 1970. Rainfall in excess of 1800 $mmyr^{-1}$ is common in the Pennine uplands on the western margin (~600 mAOD), and 600 $mmyr^{-1}$ in lowland areas of the Vale of York such as Selby (5 mAOD). The North Yorkshire Moors in the north-eastern part of the catchment receive less annual rainfall than Pennine areas, with average annual totals around 1000 $mmyr^{-1}$ common at the highest altitudes around 400 mAOD. Annual average potential evapotranspiration is 543mm

Figure 3.2: *Geology of the Yorkshire Ouse Basin*

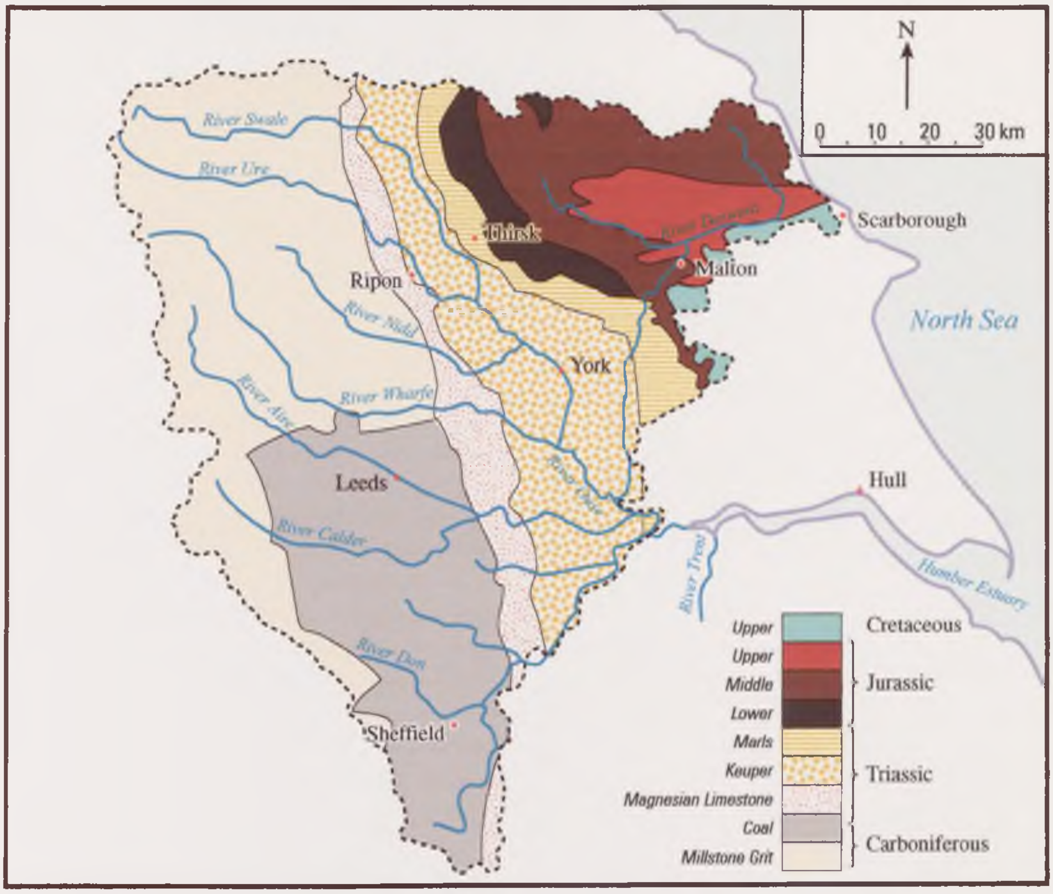


Figure 3.3: *Relief of the Yorkshire Ouse Basin*

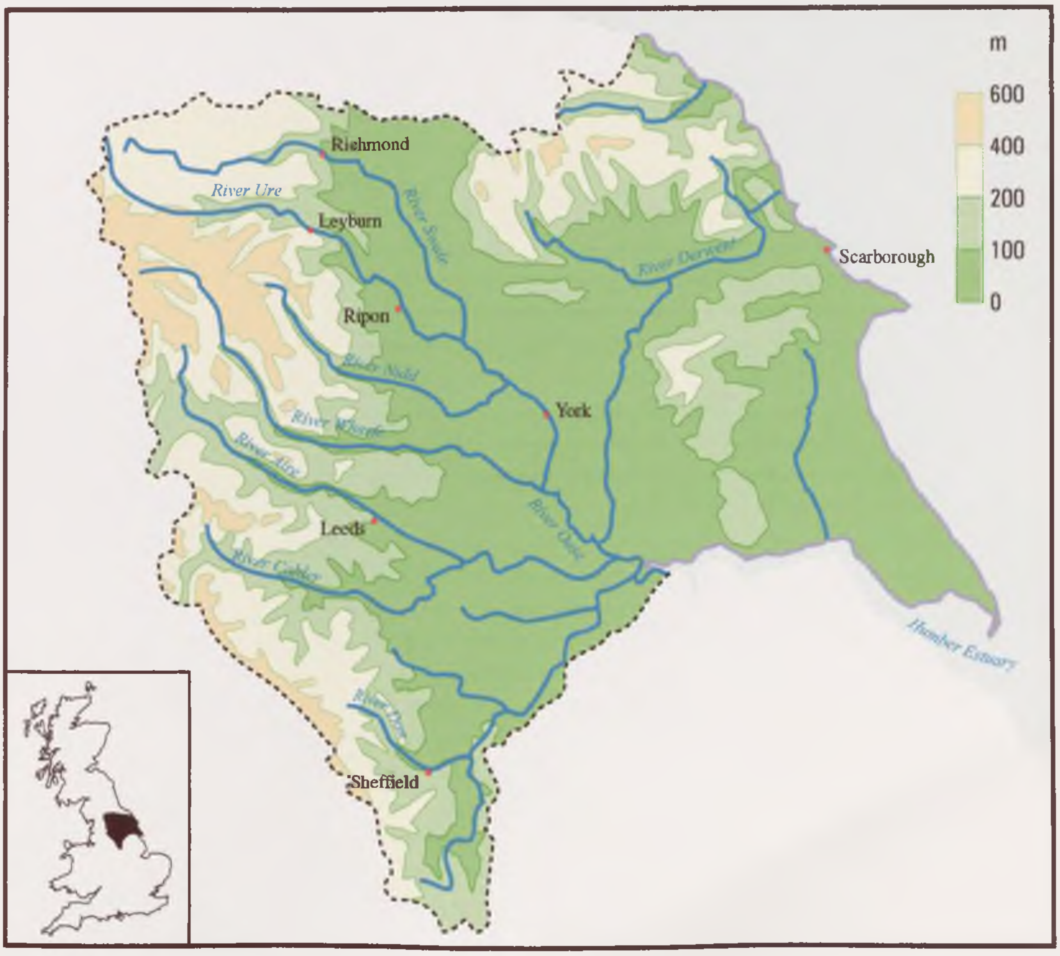
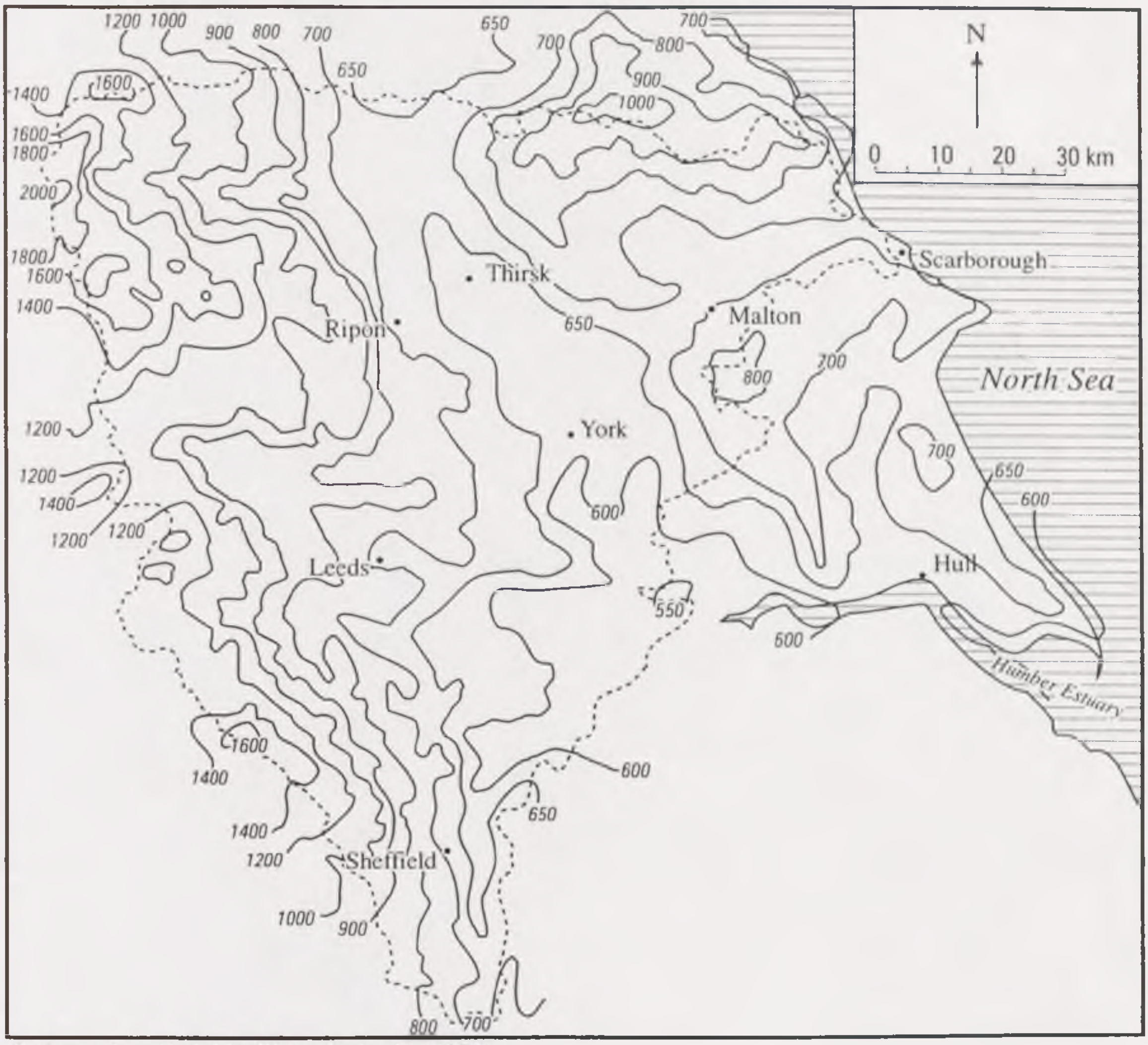


Figure 3.4: *Average annual rainfall isohyets 1941–1970*



Redrawn from Yorkshire Water Authority (1974) over the entire Yorkshire area (NRA, Ndb). In the higher altitude, wetter parts of the catchment actual evapotranspiration falls just below potential evapotranspiration during average summer conditions, whereas in the Vale of York, actual evapotranspiration falls well below potential evapotranspiration between early and late summer (NRA, Ndc). Soil moisture deficits in summer range from 80mm in the Vale of York, to 30mm in Pennine areas and 60mm over the Derwent catchment.

3.5.1. Causes of precipitation in the British Isles and Ouse basin

Barrow and Hulme (1997) identify three main causes of precipitation in the British Isles :

(1) Frontal systems
(2) Local atmospheric static instability (thunderstorms and thundershowers)
(3) Atmospheric uplift by hills and mountains (orographic precipitation)

Frontal systems are a form of cyclonic precipitation whose characteristics depend on stage of development and the type of low pressure system. The key feature of cyclonic precipitation is the 'ascent of air through horizontal convergence of airstreams in an area of low pressure' (Barry & Chorley, 1982, p93). The precipitation associated with frontal systems is spatially extensive, long duration and of moderate intensity. Rainfall receipt varies geographically over the British Isles, for example north-west Scotland receives particularly high precipitation totals due to a higher frequency of active frontal systems crossing the area from west to east, combined with orographic effects (Barrow & Hulme, 1997).

The second type of precipitation caused by local atmospheric static instability is associated with thunderstorms and generally referred to as convective precipitation. This type results from the development of convective cells due to heating of the land surface in summer (Barry & Chorley, 1982). Precipitation is often localised (20-50km^2) and of high intensity and short duration. Due to the nature of these rainfall events they are often poorly recorded (Werritty & Acreman, 1984). In central and eastern England the frequency of days of thunder are generally highest between the months of May and August (Barrow & Hulme, 1997).

A third type of precipitation in the British Isles is due to orographic influences or atmospheric uplift over mountain barriers which enhances precipitation totals on windward slopes and produces a rain-shadow effect on the leeward slopes. Barry and Chorley (1982) suggest that the intensity and frequency of winter precipitation associated with cyclones is increased due to orographic effects.

Snow is also a form of precipitation and rapid thaws or a combination of rain and snowmelt can cause severe flooding. Snowfalls over the British Isles are generated from three main sources, frontal systems, instability showers and polar lows or troughs (Barrow & Hulme, 1997). These authors suggest that in general higher altitude areas in the north and east of the British Isles receive a higher frequency of snow. Furthermore, areas such as the North Yorkshire Moors, in an easterly location and in close proximity to the coast, are more exposed to easterly, northerly, and north-easterly winds which are often snow-bearing in winter.

3.6. BASIN HYDROLOGY

3.6.1. Introduction

Long-term monthly flow data for three selected flow gauging stations in the Ouse basin shown in figure 3.5 display a typical lowland UK distribution, with higher flows in winter months, particularly between October and March, and much lower levels in the summer months. Similarly, the highest peak flows have also been recorded in winter months at these three stations. Table 3.1 shows the date of recorded peak flows at nine gauging stations, seven out of the nine show new maximum peaks have been set since the beginning of 1982, and three since 1993.

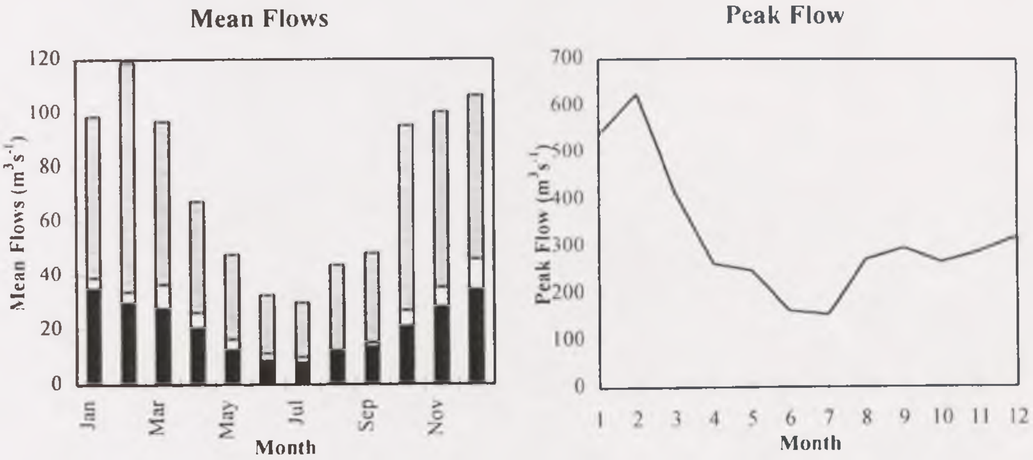
***Table 3.1** : Peak flows at selected gauging stations*

Gauging Station	Catchment Area (km^2)	Peak Flow (m^3s^{-1})	Length of Record	Date of peak flow
Swale at Crakehill	1363.0	255.70	1955-1996	7 Mar 1963
Ure at Westwick	914.6	628.60	1958-1996	1 Feb 1995
Nidd at Hunsingore Weir	484.3	310.9	1935-1996	15 Sep 1993
Wharfe at Flint Mill Weir	758.9	368.30	1955-1996	1 Feb 1995
Ouse at Skelton	3315	622.0	1969-1996	5 Jan 1982
Aire at Armley	691.5	212.4	1961-1996	19 Oct 1967
Calder at Elland	341.9	411.3	1961-1996	27 Oct 1980
Don at Doncaster	1256.0	200.50	1959-1996	23 Jun 1982
Derwent at Buttercrambe	1586.0	124.8	1973-1996	5 Jan 1982

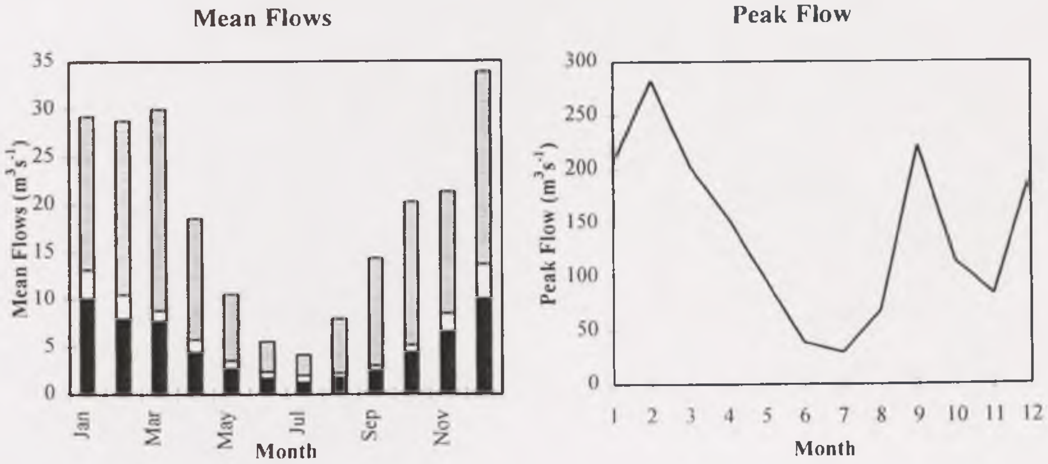
***Source** : River Flow Measuring Station Information Sheet (Institute of Hydrology)*

Figure 3.5 : *Long-term statistics of monthly mean flow and peak flow data at selected gauging sites. Mean flow diagram shows low (black), average (white) and high (grey)*

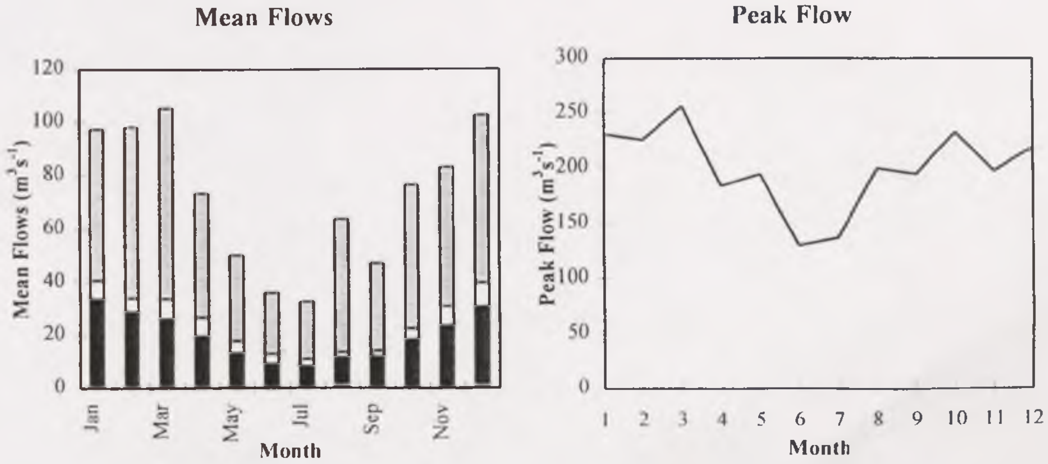
(a) : *Ure at Westwick Lock (Oct 1958 - Dec 1994)*



(b) : *Nidd at Birstwith (Apr 1975 - Dec 1994)*



(c) : *Swale at Crakehill (Nov 1955 - Dec 1994)*



Source : NERC (1996)

3.6.2. Recent flooding in the Ouse Basin

A major concern over recent years has been the apparent increase in severe flooding in the Ouse basin. In late January and early February 1995 new maximum peak flows were recorded on the River Ure at Westwick (628.6 m^3s^{-1}) and Kilgram Bridge (407.3 m^3s^{-1}), and on the Wharfe at Flint Mill (368.3 m^3s^{-1}) (Law *et al.*, 1997; Marsh & Sanderson, 1997; NERC, 1996), all of which have records in excess of thirty years. At York a 119-year flood stage record shows the largest flood to be that of January 1982 (10.12 mAOD), maximum peak flows were also recorded on the Derwent at Buttercrambe (124.8 m^3s^{-1}) and the Wharfe at Flint Mill (362.8 m^3s^{-1}). Severe flooding has also occurred at York in 1892, 1947, 1951, 1953, 1965, 1968, 1978 and 1991.

This section aims to highlight those meteorological conditions that generate extreme floods in the Ouse basin. Since the City of York has a long recorded history of flooding, it will be the focus of detailed investigations in this thesis. This section explores the climatic causes of several recent flood events in York, particularly that of January 1982.

The majority of floods at York are triggered by heavy prolonged rainfall, or a combination of snowmelt and rainfall in the winter months. Summer floods do occasionally occur at York, for example in August 1857 flooding resulted when 103mm of rain fell in York over a thirty hour period. However, the majority of severe floods are generated in winter. In 1978 heavy prolonged frontal rainfall saturated the catchment between the 24th and 28th of December, a further band of heavy frontal rainfall was rapidly converted to runoff due to the saturated antecedent conditions and resulted in a flood level of 9.85 mAOD (363.07 m^3s^{-1} at Skelton) and major disruption in the city. Although severe, this event was eclipsed only a few years later in January 1982 when flood damage was estimated at £2 million in the York area. The Environment Agency (EA) further estimated that around 540 residential and industrial properties were flooded in the city and 18700 ha of arable land were affected in the surrounding area. The flood reached a peak level at the Viking Hotel of 10.12 mAOD and a peak flow of 622.0 m^3s^{-1} at Skelton 6km upstream of York. A complex combination of weather conditions triggered the flood. First, in mid-December a series of low pressure systems delivered heavy frontal precipitation in the form of snow, figure 3.6 shows this was concentrated in Pennine areas. By the end of December low pressure systems moved in from the south, bringing milder weather and moderate rainfall. The snowpack began to thaw, and at the beginning of January a depression associated with a warm front moved over the region, accelerated the thaw and delivered heavy precipitation totals, particularly in the northern part of the basin (figure 3.7). Total precipitation over the catchment for the 25-days prior to the flood is shown in figure 3.8,

***Figure 3.6:** The 1982 Flood – Snowfall (water equivalent (mm)) 13th – 31st December 1981*

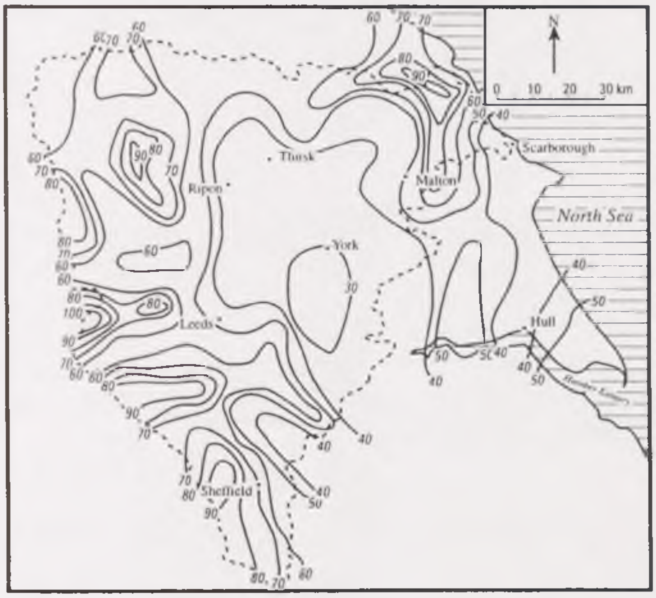


***Figure 3.7:** The 1982 Flood – Rainfall (mm) 1st – 6th January 1982*

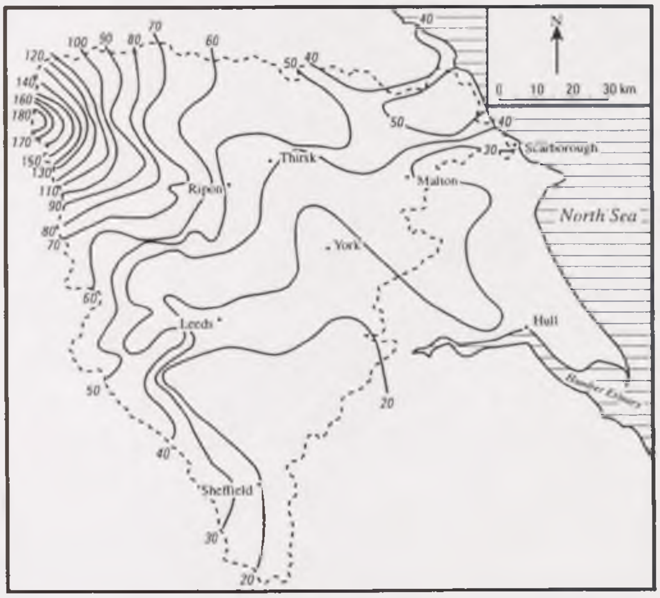
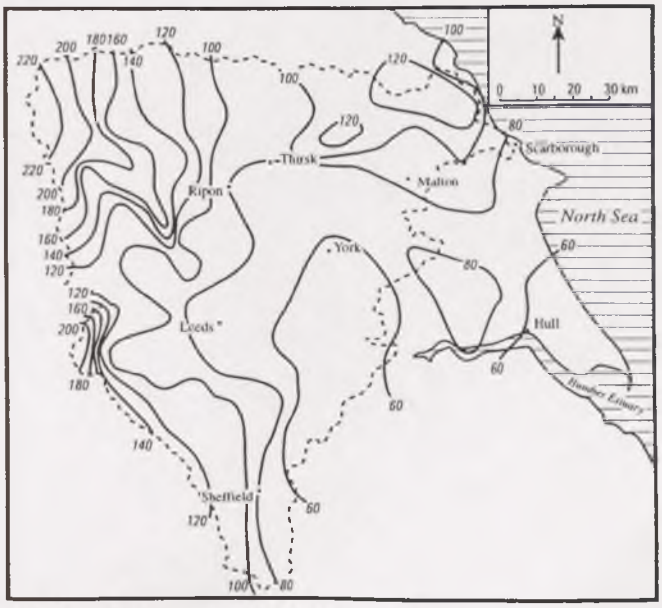


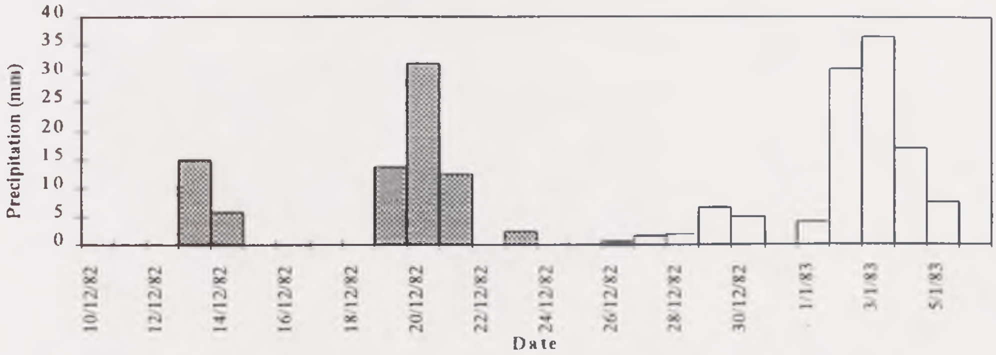
***Figure 3.8:** The 1982 Flood – Total Precipitation (mm) 13th December 1981 – 6th January 1982*



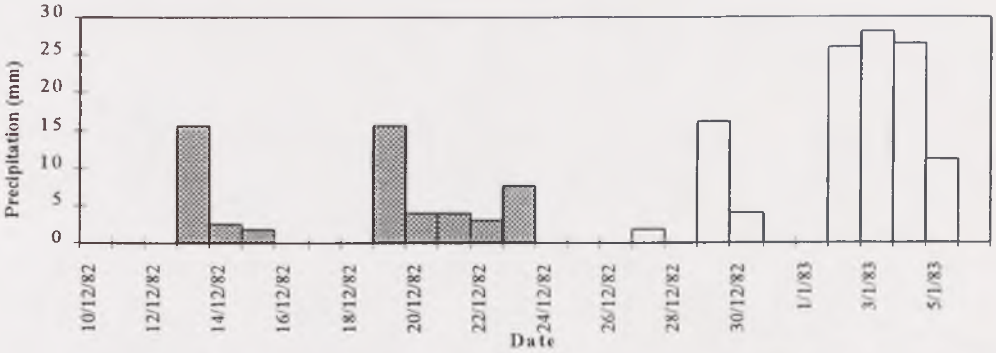
All Maps Redrawn from NRA Internal Report and at Malham Tarn and Arkengarthdale rain gauges in figure 3.9, these diagrams show very high precipitation totals in the headwaters of the northern tributaries upstream of York.

Figure 3.9 : *Precipitation prior to the 1982 flood at two sites in the Yorkshire Dales. Shaded bars indicate precipitation in the form of snow.*

(a) : Malham Tarn (SD 894 672 Alt : 395m AOD)



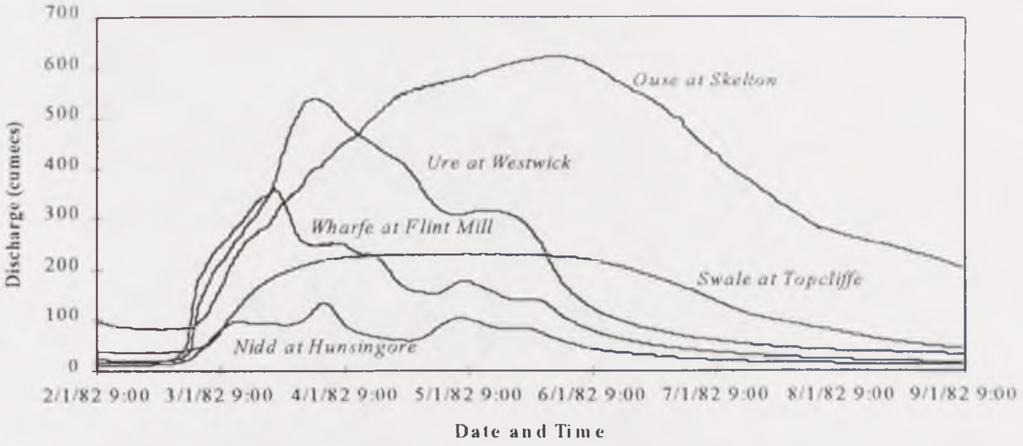
(b) : Arkengarthdale (NZ 005 025 Alt : 294m AOD)



Flood hydrographs for five gauging stations are shown in figure 3.10 and illustrate the effects reservoirs can have on flood peaks. An internal unpublished NRA report on the 1982 flood suggests that the low flood peak shown on the River Nidd at Hunsingore was the result of the attenuating effect of Angram and Gouthwaite reservoirs, which were relatively low prior to this flood. Conversely, flooding in the Boroughbridge area was exacerbated by both the unregulated Swale and Ure area peaking at the same time.

Since 1982 further severe flooding has been experienced in February 1991 at York and Boroughbridge, and in February 1995 (see above), both of which were triggered by heavy frontal rainfall on a snow covered catchment.

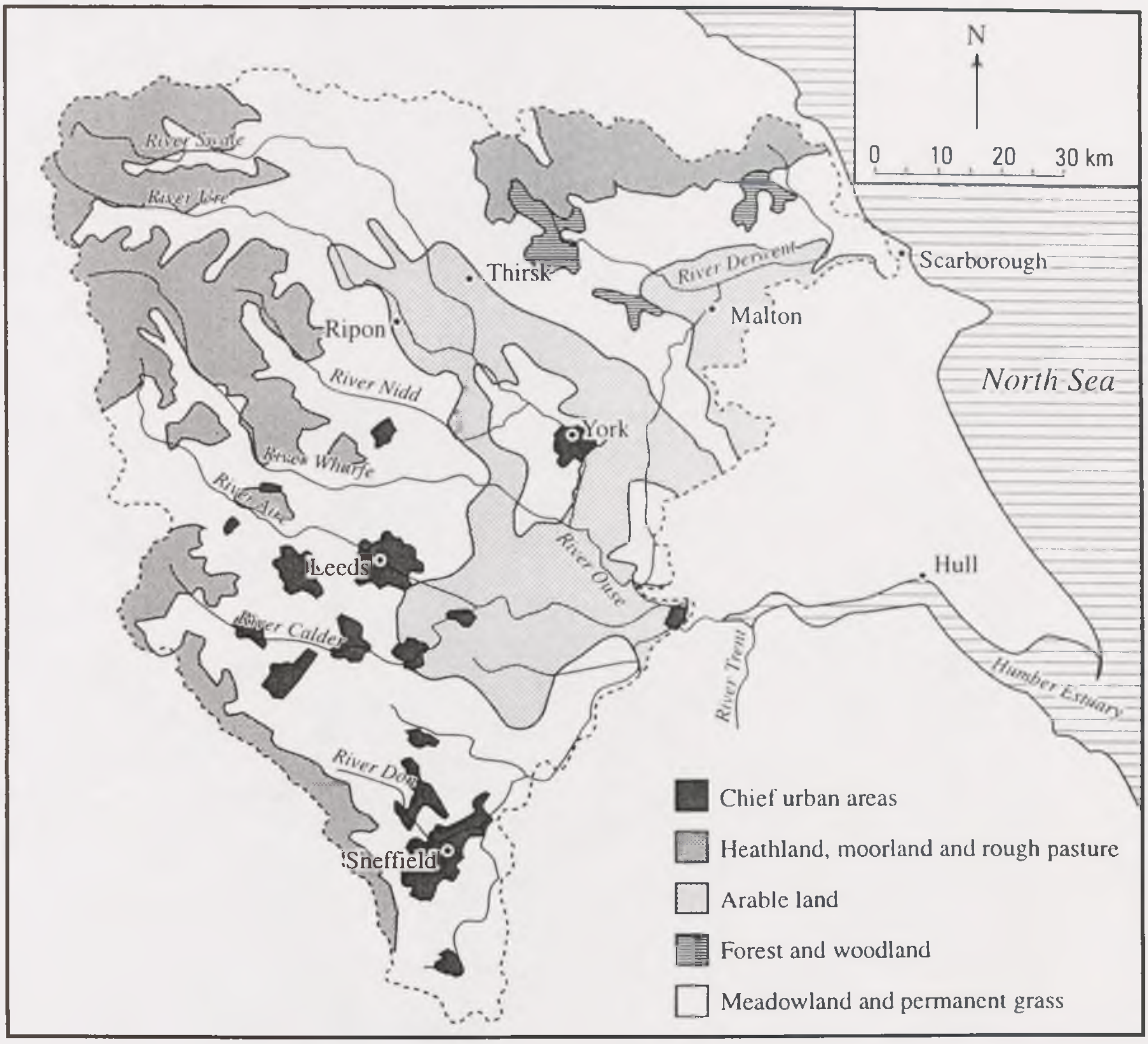
Figure 3.10 : January 1982 flood hydrograph derived from 15 minute flow data



3.7. BASIN LAND-USE

Figure 3.11 shows the principal land-use types over the Ouse basin. The Vale of York area is dominated by arable land, whereas the area between the Vale of York and the higher altitude areas is covered predominantly by permanent grassland and meadowland. The higher altitude peaks of both the Pennines and North Yorkshire Moors are composed of heathland, moorland and rough pasture. In terms of population and industry, Jarvie *et al.* (1997) make the distinction between the 'rural northern rivers' of the Derwent, Swale, Ure, Nidd and Wharfe, characterised by low population densities, and the 'southern urban industrial rivers' of the Aire, Calder and Don, which are heavily populated, with major population centres around Leeds, Bradford, and Sheffield.

***Figure 3.11:** Land-use in the Yorkshire Ouse Basin*



CHAPTER 4

FLOOD HISTORY OF THE YORKSHIRE OUSE BASIN SINCE THE ELEVENTH CENTURY

4.1. INTRODUCTION

The main objective of this chapter is to establish the spatial and temporal variability within Ouse basin flood records derived from documentary (last 900 years) and gauged (last 100 years) sources. The chapter is split in three main sections, the first investigating patterns within the gauged record, and the second dealing with documentary evidence of flooding. The final section summarises the main trends in flooding for the entire basin since the eleventh century. The results from this chapter can then be compared with spatial and temporal trends observed within climatic series (Chapter 5) and land-use records (Chapter 6).

4.2 GAUGED FLOOD HISTORIES IN THE OUSE BASIN

4.2.1. Data sources

The acquisition of suitable long-term datasets is of paramount importance in any historical study. Typically the type of data available can be split into two time periods, the instrumental period where data have been systematically recorded, and the documentary period where events are recorded on a less formal basis. The length of instrumental records varies depending on the type of data, daily rainfall records for example, are often much longer than systematic flood records. In general however, the instrumental period dates from the mid-nineteenth century, with documentary records extending many centuries prior to this.

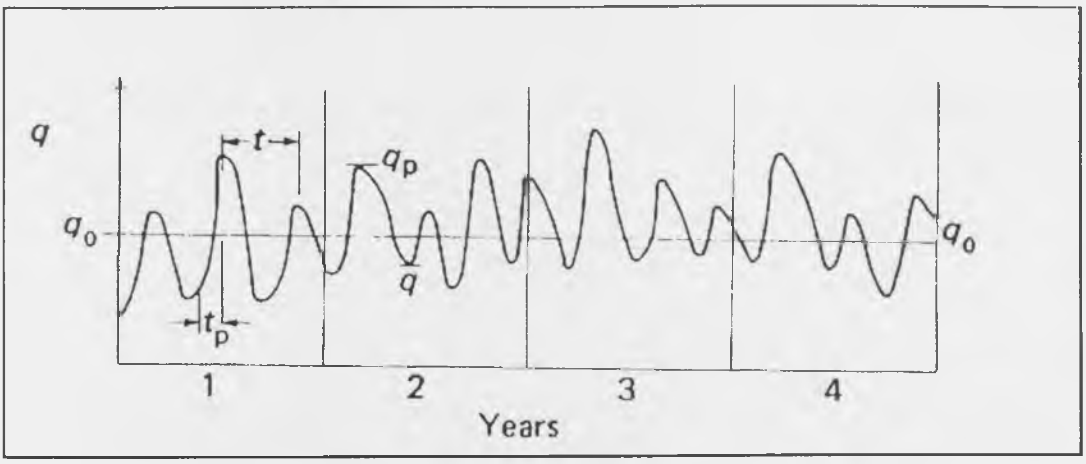
To investigate the impact of long-term environmental change on variations in flood frequency and magnitude, the most fundamental dataset required is a detailed flood history of the Ouse basin. Once any variations are established in the flood record, it is possible to address the question as to what caused these fluctuations. Historic climate (Chapter 5) and land-use records (Chapter 6) are compiled, records of daily rainfall, snow, and atmospheric circulations are used to assess climatic links, and records of agricultural land-use, land drainage, reservoir construction, and direct channel alterations, to assess any land-use influences. The temporal coverage of records compiled for the Ouse basin extend over the instrumental and documentary period, whereas the spatial coverage is limited by the location of LOIS designated study sites (see section 1.3), particularly over the instrumental period. This section describes how data were collected, and databases of instrumental and documentary floods compiled.

The Hydrological Data UK Yearbook 1994 (NERC, 1995) calculated that the average length of flow record held in the National River Flow Archive was less than 23 years, and only 15 stations could be considered continuous for a period of over 50 years. The majority of gauging station records do not commence until the 1960s, indeed, it was not until 1948 that rivers boards were required to operate gauging stations at all (Hooke and Kain, 1982). A detailed review of the history of river flow gauging in the UK is given by Lees (1987), who suggests that only a small number of rivers in the UK have gauged records which date back to the nineteenth century, examples being the Lee at Fieldes Weir (from 1851), the Thames at Teddington (from 1883) and the Severn at Bewdley (from 1879). In the Ouse basin records have been compiled from various sources that date back to 1878 (Ouse at York), 1868 (Don at Doncaster), 1863 (Calder at Broadreach) and 1864 (Aire and Calder at Castleford), however some of these records have significant gaps or have not been updated since the publication of the Flood Studies Report (NERC, 1975). Typically gauging starts around the 1950s and 1960s in the Ouse basin, however the longer 'gauged' records represent an as yet unexplored source of long-term flood data.

Two types of flood record can be compiled from continuous flow data, an annual maximum (AM) series and a peaks over threshold (POT) series, sometimes referred to as a partial duration series. Constructing an AM series simply involves extracting the highest recorded stage or discharge for each year records are available. POT series are more complicated to compile, since each flood in the series above a specified threshold must obey the rules of independence defined by NERC (1975). These state firstly, that the discharge of a given flood must fall by a minimum of one-third of its peak before rising to another, and secondly, that the time between successive flood peaks must be at least three times the mean time to peak at the gauging station. These rules ensure statistical independence between flood events and are summarised in figure 4.1.

Figure 4.1 : *Rules of independence for a POT series (from Shaw, 1994) -*

$t > 3t_p$ and $q < \frac{2}{3}q_p$



Both AM and POT series are used in this study since information is required on both the frequency and magnitude of flooding. AM series only provide flood magnitude information whereas, both frequency and magnitude can be extracted from a POT database, however, by using both series, different aspects of flood magnitude can be investigated.

AM and POT data were initially obtained from the Institute of Hydrology (IH) for the gauging stations listed in table 4.1. These sites were chosen since they represent the longest flood records on each of the major lowland tributaries of the Ouse basin and were in close proximity to the primary LOIS study sites. However, much of the data from IH needed to be updated to 1996 since many of the records ended around 1982. Post-1982 continuous flow data are held by the Environment Agency on their HYDROLOG Data Management System at both Leeds and York offices. Updating the AM series was a simple task which can be quickly and easily output, directly from the HYDROLOG system. Updating a POT series is a more complex process since the rules of independence (NERC, 1975) must be obeyed, and a threshold set prior to extraction. The data obtained from IH had a pre-set threshold which had been chosen to give on average, five peaks per year, however, this threshold was based on the period of record being analysed at the time of data extraction, and not necessarily a standard time period. This could cause problems since records extracted in a particularly wet period may have a higher relative threshold than those extracted during a particularly dry period with relatively little flooding (Bayliss, pers. comm.). It was therefore decided that new thresholds should be set for each site based on a standard time period allowing for more reliable inter-site comparison. A great deal of previous work on this subject has been carried out on Scottish rivers (e.g. Acreman, 1985a; Black, 1992; Grew, 1996), and in the most recent study by Grew (1996) the standard threshold adopted was an average of 4.5 flood events per year over the ten year period 1979-1988, which complies with the recommendations of the Flood Studies Report (NERC, 1975). This period has also been used in this study in order to allow comparisons with the sites in northern England and Scotland Clearly, the majority of records from IH for the Ouse basin did not cover the period 1979-1988, therefore the threshold set by IH had to be used for initial extraction from the EA database. Once the initial threshold was set flow data were extracted from the HYDROLOG system specifying zero days independence, therefore giving every day the threshold was exceeded. Independence of flood peaks was than evaluated by viewing 15 minute flow data on computer screen at the Leeds EA Office. In order to comply with the independence rules a 'time to peak' had to be calculated for each of the individual gauging stations. The method used by Black (1992) has been adopted here, whereby for each station the time to peak for the first five peaks in the record to be studied were noted, and the average value taken as the 'time to peak' at that site. Flood peaks which satisfied both the rules of independence (outlined in figure 4.1) were then extracted and added to the existing IH data. All peaks were included upto the end of December 1996. Once this task was complete the standard threshold could be set for the period 1979-1988 to have exactly 45 flood events, and the final POT series compiled. All sites, standard thresholds and summary information are shown in table 4.1, and their location given in figure 4.2.

The longest continuous record of flooding in the Ouse basin is at York (SE 602 517), however, this site is not a principal gauging station, and only stage data are available (crude rating curves have been derived for the Guildhall (figure 4.3(a)) and Ouse Bridge (figure 4.3(b)) recording sites (see below), although, these curves are based on very few measurements, particularly at higher discharges, therefore flood stage has not been converted to discharge). The earliest records of flood stage in York begin in 1831 and were recorded by the Town Clerks Office at Ouse Bridge (datum 4.97m AOD) opposite King's Staithe, however the record between 1831 and 1878 cannot be considered systematic, since floods were noted in passing or derived from historical sources. Systematic gauging began in 1878 with all floods above 8.03m AOD (10ft above summer level) being recorded, these records were compiled by Farrant (1953) and subsequently updated by the NRA and EA. Between 1893 and 1968 the Guildhall gaugeboard (datum 4.98m AOD) was used for recording, and from 1969 onwards a Munro water level recorder and metric gaugeboard (datum 5.00m AOD) has been in use situated near the Viking Hotel. The fact that the sites are only 200m apart enables us to assume that the record is continuous and systematic since 1878, with more *ad-hoc* stage recording dating back to 1831. Establishing the independence of flood peaks was a difficult task since many of the early records have been lost (Mott, Hay & Anderson and Sir M. Macdonald & Partners, 1982), however, simply viewing the record and dates of flood events suggests that these peaks are independent since consecutive days of data do not appear in the record. Stability of channel

Figure 4.2: *Location of LOIS study sites, flow guaging station and historic flood recording sites*

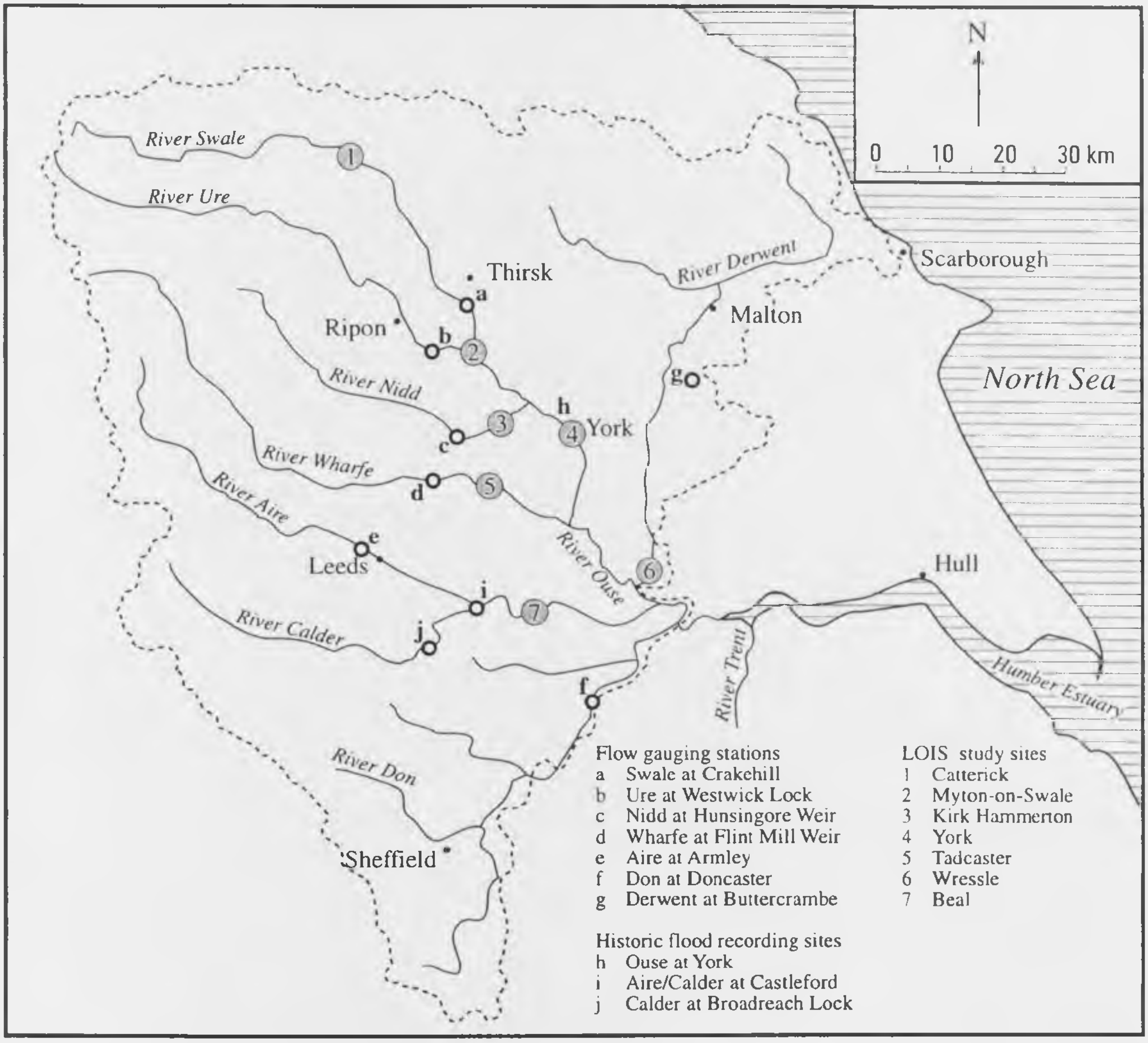


Table 4.1 : *Flow gauging stations used for analysis*

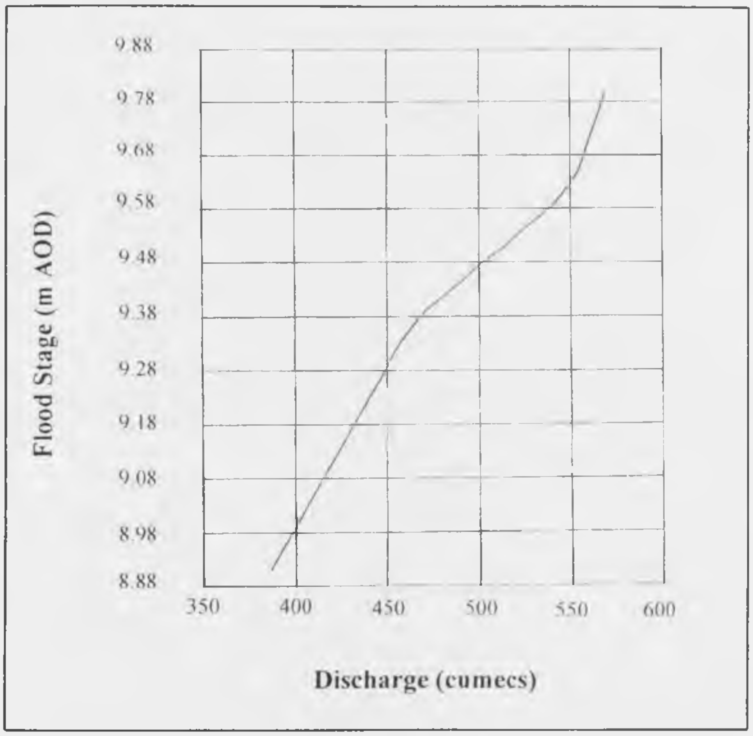
(IH Station No.) Station Name	Grid Ref	Level (mAOD)	Catch Area (km^2)	Max Alt (mAOD)	Standard Threshold (m^{3}s^{-1})	Length of Record	Years of AM Data Missing	Years of POT Data Missing	Peak Flow (m^{3}s^{-1})
(27001) Nidd @ Hunsingore	SE 428 530	18.1	484.3	704	66.50	1934-1996	0	0	310.9
(27002) Wharfe @ Flint Mill	SE 422 473	13.7	758.9	704	163.00	1936-1996	0	0	362.8
(27007) Ure @ Westwick	SE 356 671	14.2	914.6	713	168.70	1956-1996	0	0	625.9
(27021) Don @ Doncaster	SE 569 040	4.4	1256.0	247	112.60	1868-1996	16	28	200.5
(27028) Aire @ Armley	SE 281 340	26.1	691.5	594	98.40	1961-1996	1	0	212.4
(27041) Derwent @ Buttercrambe	SE 731 587	9.5	1586.0	454	58.70	1962-1996	0	0	124.8
(27071) Swale @ Crakehill	SE 425 734	12.0	1363.0	713	124.50	1955-1996	0	0	255.7
Ouse @ York *	SE 602 517	5.0	3315	713	8.03 **	1878-1995	0	0	622.0 (Skelton)
Aire & Clader @ Castleford *	SE 425 263	-	1840						
Calder @ Broadreach *	SE 352 211	-	-						

* Not a principal IH gauging station

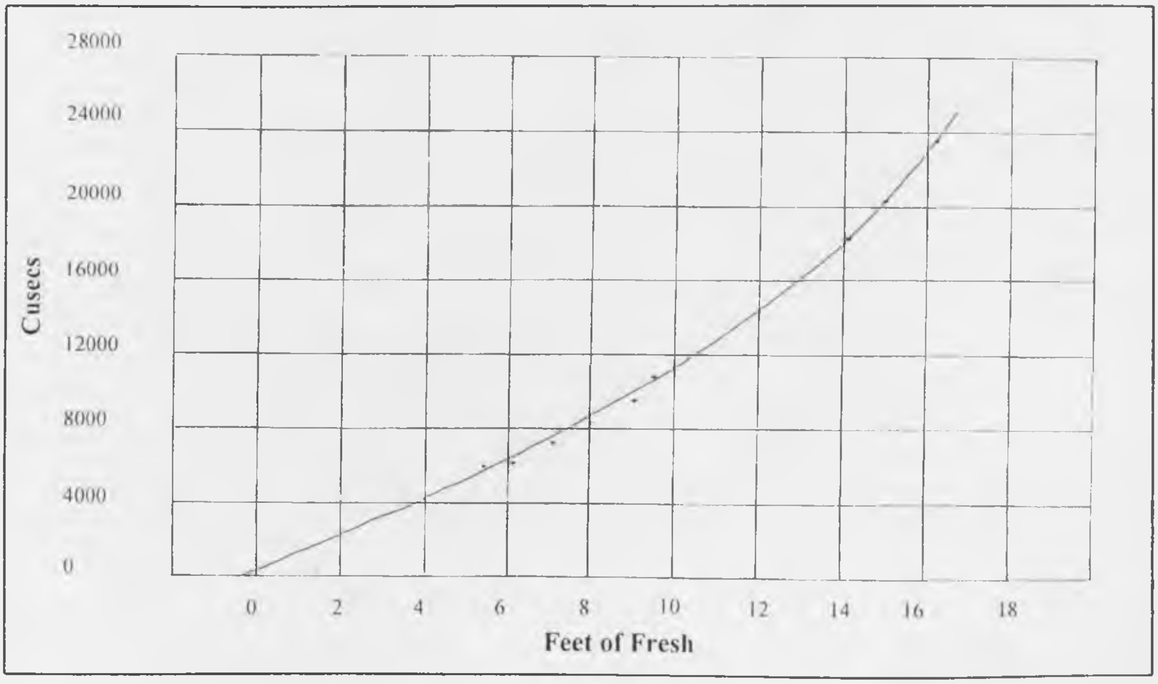
** Stage record (m AOD)

Figure 4.3 : *Stage-discharge relationship : (a) Guildhall Recorder York (EA Dales Office) (b) Ouse Bridge York (Farrant, 1953)*

(a)

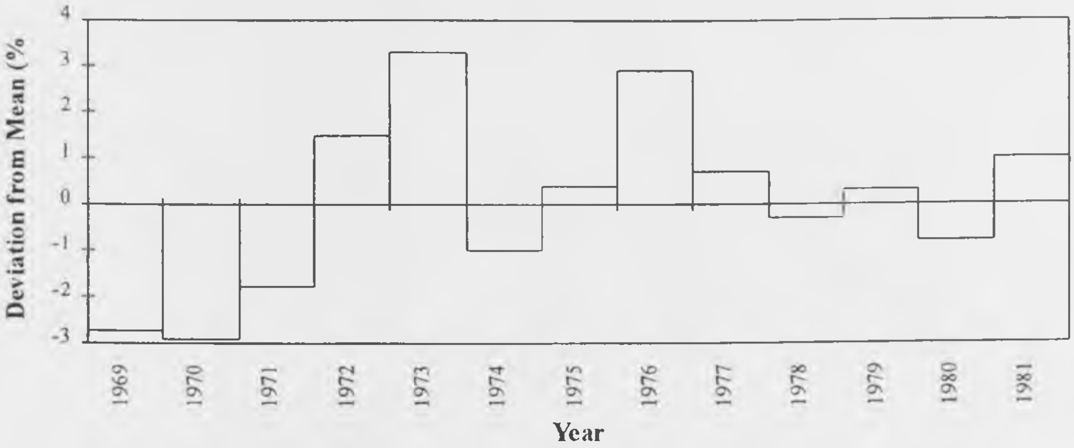


(b)



cross-section at the stage recorders is difficult to assess, however, between 1969 and 1982 the Yorkshire Water Authority took hydrographic surveys of the River Ouse three times a year between Naburn and Poppleton (figure 4.4). These surveys show that there has been no significant trend in cross sectional area over this period (only ±3% of the mean) although these records are too short to draw firm conclusions. POT and AM series have been updated to 1996 for the Ouse at York from paper charts at York Environment Agency and more recently from a digital recorder which has been installed near the Viking Hotel.

Figure 4.4 : *Mean annual cross-sectional area 1969-1981 - River Ouse at York. Source, Mott, Hay & Anderson and Sir M. Macdonald & Partners, (1982)*



Problems with gauged data

1. Some of the records contained substantial gaps which could cause problems at the analysis stage. For example the Don at Doncaster has a 28 year gap between 1932 and 1960 in a POT series dating from 1868, and more sporadic gaps in the AM record. An attempt was made to find the original charts for this site, however, due to the then National Rivers Authority moving offices several times, the whereabouts of old records has been difficult to establish resulting in these large gaps remaining in the data.

2. A second problem with updating records was encountered with two AM series which were published in the Flood Studies Report (NERC, 1975) historical section. The records for the Calder at Broadreach (1864-1968) and the Aire and Calder at Castleford (1863-1968) have not been updated from 1968 since the original source material could not be located. The Environment Agency has been unable to find any reference to these two sites in their records. However, these two series are still included in the analysis since they provided valuable long-term information which can be compared to other sites in the Ouse basin such as York.

3 Certain sites such as the Calder at Elland were initially identified as possible sites for analysis, however closer inspection of the records revealed that different flow parameters had been recorded over different periods. Data under the `flow` parameter were available for this site from 1953, however, between 1973 and 1981 this changed to 'daily flow', then back to 'flow' from 1982 onwards. It is important to recognise the difference between these two parameters, 'flow' gives the instantaneous daily maximum, whereas, 'daily flow` gives an average discharge for the whole water day. Clearly, mixing the two data sets could lead to misinterpretation of apparent trends within a particular data set.

4. Some sites may not be suitable for the analysis of long-term trends since the flood peak may be severely truncated due to the banks being overtopped during a flood event, for example, the River Aire at Beal

4.2.2. Preparation of gauged flood data

Annual maximum (AM) and Peak over threshold (POT) series have been compiled from the sources outlined above. The patterns within both types of flood record have been analysed to explain recent (last 100 years) variations in flood frequency, magnitude and seasonality. The flood records considered represent the longest gauged sites available for each major tributary in the Ouse basin, with a secondary consideration given to the proximity of primary LOIS study sites where Holocene floodplain histories have been evaluated.

One of the simplest techniques used to investigate variations in flood records involves creating annual series for both flood frequency and magnitude. Clearly, AM data need no preparation since only the highest magnitude event for each year is recorded, POT data however, require a degree of manipulation prior to analysis. Annual flood frequency (AFF) series can be compiled from POT data simply by calculating the annual number of POT events over the standard threshold defined for each site, as explained in the previous section. Magnitude data can also be compiled on an annual basis using a technique recommended by Naden (1992), which gives the annual 'mean exceedance' of a POT series above the standard threshold. This technique has been used by Grew (1996) to produce magnitude series for a large number of Scottish rivers, she states that the advantage of this method is that the annual value is specified relative to discharge threshold. The annual mean exceedance (AME) has been calculated for each site with POT data using the following formula :

$$\text{Annual mean exceedance} = \frac{\sum_{i=1}^{n} (di - T)}{n}$$

where

di = discharge of POT event

T = POT threshold

n = annual frequency of POT events

4.2.3. Techniques of data analysis

Simple time series, non-parametric statistics and flood frequency analyses have been used to investigate variations in the three types of annual flood record available for analysis; annual maximum (AM) series, annual mean exceedance (AME) and annual flood frequency (AFF) The following section outlines the principles of each of these techniques and how they can be applied to the analysis of flood records.

Time series analysis

To investigate the temporal behaviour in flood records, graphical time series plots have been produced for each site showing both AM and POT derived data, these series are shown in figures 4.5 - 4.7 and have been smoothed using a simple 5-year moving average. The long term average is also plotted on each diagram to give an indication of overall trends, and relative variations over time, particularly periods of increased or decreased flood magnitude or frequency.

Statistical analysis

A number of basic summary statistics and two simple statistical tests (a Runs Test which tests for randomness in a time series and the Kruskal-Wallis test, which tests the statistical equality of three or more periods) have been used on the AM and POT flood data.

To determine whether or not a time series is statistically random, the Run Chart function in MINITAB has been employed. Two tests for non-random behaviour are calculated using this function. The first involves testing the number of runs that occur both above and below the median, where a run is defined as 'one of more consecutive points on the same side of the median' (MINITAB Reference Manual, 1996. p9-4). A test statistic is calculated and the normal distribution used to give two *p*-values, which can indicate mixing (two processes operating at different levels) or clustering of data. For the test to be significant at the 5% level, one of the calculated *p*-values must be less that 0.05; this being the case, then the null hypothesis (H_o) of a purely random series can be rejected in favour of a non-random time series due to either mixed or clustered data points.

The Run Chart function can also test for the number of runs up or down, where, in this case a run is defined as 'one or more consecutive points in the same direction' (MINITAB reference Manual, 1996, p9-5). This test is sensitive to two types of non-random behaviour, trends and oscillations, where an oscillation suggests the data fluctuate up and down rapidly, and a trend suggests a 'sustained and systematic source of variation where the data tends to move or drift in the same direction' (MINITAB reference Manual, 1996, p9-6). Again the null hypothesis is that the data are a statistically random series. *P*-values and significance levels are calculated as above, and H_o can be rejected if either value is less than 0.05.

The second statistical test employed is the Kruskal-Wallis test, which is a nonparametric technique that can be used to test whether certain sub-periods are statistically equal. The null hypothesis is that there is no difference between populations tested. This technique has been used to test for any statistical difference between 5-year periods for AM, AME and AFF data where 5-year periods have been standardised to end in 1996. A *H*-statistic is calculated, and *p*-value given. Where *p*-values lower than 0.05 indicate that there is a statistical difference between 5-year periods significant at the 5% level.

Flood frequency analysis

Flood frequency analysis is often used for engineering purposes when designing structures such as bridges, dam spillways and flood protection works. The technique uses past flood records in order to predict future flood-magnitude relationships, assuming that the flood regime has been stationary through time. Flood frequency analysis estimates the relationship between flood discharge Q and return period T, where T is the time on average that elapses between two events of equal magnitude (Wilson, 1990). Different models can be used to establish frequency-magnitude (Q-T) relationships for AM and POT data since each have distinct statistical properties.

In this study the POT model is applied to flood and climate data. Discharge or rainfall estimates for various return periods have been calculated and used to set a series of increasing thresholds for individual sites, to investigate the timing of specific magnitude events. Estimates of discharge for the 100-year flood (Q_{100}) and 100-year rainfall are also calculated on a seasonal basis, which enables specific seasons to be identified as generating higher magnitude flood events.

The POT model

Estimation of the Q-T relationship for POT data uses all independent peaks over a set threshold q_o. This threshold can dictate how well the model fits the flood data (Grew, 1996) and therefore must be given careful consideration before proceeding with the analysis. The mean annual number of floods (λ) which exceed q_o is given by the equation :

$$\lambda = \frac{M}{N}$$

where

M = number of peaks in POT series

N = number of years in POT series

Naden (1992) used log-survivor functions and mean excess plots to argue that to obtain the best fit for the POT model the mean number of floods per year (λ) should be set to 3.0 or less. Consequently, Grew (1996) used $\lambda = 2.0$, a value which Cunnane (1989) suggests gives the most satisfactory exponential distribution fit. For these reasons a value of $\lambda = 2.0$ was chosen in this study and the discharge threshold q_o raised accordingly for each site. Once a new threshold had been set, assuming an average of two peaks per year over the whole period to be analysed, the return period of each event in the series is calculated using the Weibull equation below :

$$T = \frac{n+1}{m}$$

where

T = Return period

n = number of events

m = rank of event

The relationship can be plotted as a straight line by using a linear scale for discharge, and calculating plotting positions, or reduced variate values of T using the following equation :

$$y = \ln(\lambda\ T)$$

Discharge estimates of the T year flood can than be calculated from :

$$Q_T = q_o + \beta\ \ln(\lambda\ T)$$

where

β = standard deviation of POT data

$$q_0 = q_{\min} - \frac{\beta}{M}$$

q_{min} is the smallest discharge which exceeds the new threshold where $\lambda = 2$

Analysis of flood seasonality

In any investigation into seasonality of flooding there must be a clear definition of which months relate to each season, which can vary depending on the time periods into which the year is to be split. Two different monthly groupings have been used. Firstly, the year is split into 2-monthly periods from, June-July, August-September etc. The splits have been used for flood frequency analysis of seasonality and to investigate the frequency of floods in particular months over the whole period of record at a particular site.

The second, more standard grouping of months, uses three monthly periods, where December-February are classed as winter, March-May as spring, June-August as summer, and September-November as autumn. Annual flood frequencies for each season have been calculated from POT records to establish temporal changes in seasonality. A slightly different approach is taken when plotting the seasonality of AM floods. In this case plots have been produced which show the day of each annual peak, where the 1st June of each year is taken to be day zero. This avoids splitting the record over the winter period, when most floods occur, which would be the case if conventional calendar days were used.

4.2.4. Variability in flood frequency, magnitude and seasonality in the Ouse basin

4.2.4.1. Gauging station histories

Prior to any analysis of long-term hydrological series it is essential to assess whether any non-stationarities exist within the history of the gauging station. Obviously, the further back in time flood records extend, the data are more prone to uncertainties such as stability of cross-section and reliability of measurement and collection techniques. Station histories at principal gauging stations have been assessed from Institute of Hydrology River Flow Measuring Station Information Sheets. However, assessing historic sites, where gauging was done on a less formal basis such as the Ouse at York, Aire and Calder at Castleford and the Calder at Broadreach is a more difficult and sometimes an impossible task.

The two sites on the Aire and Calder which date to the nineteenth century were compiled in the Flood Studies Report (NERC, 1975). However, there is no indication of how these readings were taken, or history of the site. Nevertheless, since these sites represent the only long-term quantitative evidence of flooding on these tributaries, they have been included in the analysis stage. At York, on the other hand, a detailed history of gauging is available and has been described is section 4.2.1. However, even in this case, cross-section stability has only been evaluated since 1969 (figure 4 4).

The station histories at the remaining sites, all principal gauging stations, suggest non-stationarities at several sites, which must be taken into consideration Pre-1965 data on the Wharfe at Flint Mill, and pre-1971 data on the Aire at Armley, are considered to be less reliable than later measurements. More significantly, however, the station summaries document that the gauging site has been shifted at two of the stations. On the Swale at Crakehill flows prior to 1980 were measured at Leckby Grange with a catchment area of 1345.6 km^2, compared to 1363.0 km^2 at Crakehill. Similarly, pre-1973 data for the Derwent at Buttercrambe was gauged at Stamford Bridge, in this case however, there is only a negligible difference in catchment area. Clearly, if major variations are evident in these flood records at these critical dates, then both records must be considered suspect for analysis.

4.2.4.2. Annual maximum series (AM)

Table 4.2 shows the basic summary statistics of the ten sites selected for analysis in this section, and their locations are shown in figure 4.2. Records are of variable length, the oldest record dating to 1863 on the River Calder at Broadreach, and the most recent, on the Derwent dating to 1962. Tests for randomness were carried out on each AM series, using MINITAB's Run Chart function (section 4.2.3.), the results displayed in table 4.3 show only two sites, the Ouse at York and the Aire and Calder at Castleford, to be statistically non-random series at the 5% level, both tests suggesting clustering of data. However, the apparent random nature of the other AM series indicated by the Run Chart results could be accounted for by the fact that flood series, by their very nature, often show very high inter-annual variation. There may still be a general upward or downward tendency within these variations, however, a runs test will not show this to be significant since flood series will often vary considerably about the mean. Therefore, this may not always be the most suitable test for trends within a flood series.

The longest AM records available are, the Calder at Broadreach (1863-1968), the Aire and Calder at Castleford (1864-1968), the Don at Doncaster (1868-1996), and the Ouse at York (1880-1995). There are a number of problems with some of these AM series which have been discussed in section 4.2.1. To recap briefly, it has been impossible to update both the Aire and Calder records from 1968, and there is a significant gap in the Don record. Clearly, the flood record at the Viking Hotel in York represents the longest continuous flood series in the Ouse basin, and is worthy of detailed investigation The following section describes the York record in detail, the long Aire, Calder and Don records together, and the remaining shorter records separately.

Long-term records of flood magnitude :

The Ouse at Viking Hotel - York

Figure 4.5 (a) shows the AM stage series at York since 1880, runs tests (table 4.3) suggest that this is a non-random series significant at the 0.5% level. Similarly, a Kruskall-Wallis test on the standard 5-year periods (table 4.4) show that there is significant difference between 5-year periods at the 1% level.

The AM series at York indicate that the period 1880-1903 was characterised by magnitudes fairly close to the long-term mean, this trend only interrupted by the flood event of 1892 There followed a period of extremely low flood magnitudes in the early part of the twentieth century, until around 1915. From 1915 onwards there has been a 15-20 year 'saw-tooth' like cycle with progressively increasing stage which peaked in the early 1980s. Indeed, the highest flood magnitudes over the whole period have occurred since 1977, with the two highest 5-year period averages being 1977-1981 (9.23m AOD) and 1992-1996 (9.07m AOD). Within this 'saw-tooth' cycle there are a series of peaks and troughs, with peaks in magnitude occurring in the late 1940s, mid-to-late 1960s, late 1970s to early 1980s and the early 1990s. Periods of low magnitude occurred between 1902-1906 (the lowest on record), in early 1930s, early 1950s, and the early-to-mid 1970s.

The Aire, Calder and Don

The three other long AM flood series are shown in figures 4.5(b) - 4.5(d). The Calder at Broadreach (figure 4.5(b)) is very different to the Ouse record at York. The highest flood magnitudes occurred in the late nineteenth century, with a long and gradual decline evident since around 1903. The highest average magnitudes occurred in the 1877-1881 5-year period, and the lowest after the 1940s. More recent changes in flood magnitude, however, cannot be evaluated since this record only extends to 1968.

The Aire and Calder at Castleford (figure 4.5(c)) illustrate similar trends to those observed on the Ouse at York for the period of record available (1864-1968), although the highest magnitudes are again evident in the late nineteenth century. As with the Calder at Broadreach, there is a clear and marked decline in flood magnitudes from around 1900 to 1920. A further period of low magnitudes in the early to mid 1950s and higher magnitudes in the late 1960s is also common to both the Ouse and Aire records

The Don at Doncaster AM record (figure 4.5(d)) must be interpreted with caution because 16 years of the 129 year record are missing, however, several interesting trends are still evident. Again the late nineteenth century appears to be characterised by high flood magnitudes, which declined and remained low over the period 1900-1920. There then followed a series a large flood events on the Don between 1920 and 1948, some of the largest on record occurring in 1931, 1941 and 1946. Lower magnitude floods were more common after this period except in the late 1960s when magnitudes increased slightly.

Summary of long-term records of flood magnitude : 1863-1996

This period encompasses the longest flood records in the Ouse basin and problems common to many historical records arise, such as gaps in the data, reliability of measurements, and updating old records. Nevertheless, after taking these factors into consideration several of these records display similar trends. The three records that extend back to the 1860s (Aire and Calder at Castleford, Calder at Broadreach, and the Don at Doncaster) all show that the late nineteenth century was characterised by high flood magnitudes, which experienced a marked decline at the turn of the present century. This is also evident, to a lesser extent, on the Ouse at York. Low flood magnitudes dominated until around the 1920s, when the situation becomes more complex and individual sites start to show significant variation. The Calder at Broadreach shows a small increase in magnitudes in the 1920s and then a steady decline to the end of the record (1968). Whereas, the Ouse at York, and the Aire and Calder at Castleford, exhibit similar peaks and troughs in the post-1920 period, with high magnitudes in the late 1960s and low magnitudes in the early to mid 1950s. The Don at Doncaster is similar to the Ouse record from the 1950s onwards, however, prior to this period the highest magnitudes on record for the River Don occurred between the 1920s and 1940s.

Recent records of flood magnitude : 1936-1996

Two of the oldest, complete and continuously gauged records of discharge in the Ouse basin are the Nidd at Hunsingore and the Wharfe at Flint Mill which are both broad-crested weir gauging stations. AM series are shown in figures 4.5(e) and 4.5(f) respectively, and display a series of synchronous peaks and troughs in magnitude. The 5-year running means show high flood magnitudes at both sites in the mid to late 1940s, mid to late 1960s, the early 1980s and the 1990s. The relative magnitude of these peaks does however differ between the two sites, the highest 5-year average AM value (table 5.3) occurring in 1947-1951 on the Wharfe, and in

1992-1996 on the Nidd. Common periods of low flood magnitude are evident in both records in the 1930s, 1950s, early to mid 1970s, and the mid-to-late 1980s. The 5-year period with the lowest magnitudes is 1972-1976 at both sites The timing of peaks and troughs in these records correspond closely to the variations observed in the York AM series, with a similar cyclic pattern shown at all three sites. However, the Wharfe at Flint Mill shows flood discharge to be progressively decreasing in 15-20 year cycles, the opposite to the trend at York. In contrast, the Nidd at Hunsingore shows a progressively increasing discharge with the most recent period displaying the highest flood magnitudes. Runs tests indicate AM records at both sites are statistically random time series. There is also no significant difference between 5-year periods shown by the Kruskall-Wallis test.

The four other gauging stations that have been studied have the shortest records of flood magnitude and frequency. Two are gauged at broad-crested weirs, the Ure at Westwick Lock and the Aire at Armley, and the other two are gauged at crump weirs, the Derwent at Buttercrambe and the Swale at Crakehill (figures 4.5(g) - 4.5(j)). Each of these records display some similarities in the timing and direction of flood magnitude changes discussed at the previous sites, however there are significant variations in some cases. Peaks in flood magnitude are synchronous at all four sites in the mid-to-late 1960s, early-1980s, and in the 1990s, with the exception of the Derwent at Buttercrambe where , although flood magnitudes do increase slightly after the mid-1980s low, this is not on the scale of the other three sites. Periods of low flood magnitude in the early-to-mid 1970s and mid-1980s are also broadly similar, however, there are inter-site variations in the most recent period. The Swale at Crakehill and the Ure at Westwick show high flood magnitudes in the 1990s, whereas the sites on the Aire and Derwent show a fall in flood magnitude. In terms of 5-year averages (table 4.4), the Ure, Aire and Swale all show the lowest magnitude in the period 1972-1976, and the Derwent in 1987-1991. Periods of highest flood magnitude are more variable, highest averages on the Swale and Ure occur in 1992-1996, on the Aire in 1982-1986 and the Derwent in 1987-1991. On the Ure at Westwick there have been a series of three extremely large flood events, in 1982, 1991 and 1995 which appear disproportionately large compared to other floods in the series, and no other site shows such a degree of variation. This may reflect errors in discharge measurement, or a significant land-use change in the Ure catchment (which has been suggested by the NRA, see Sansom, 1996). All four time series are considered to be statistically random from Runs Test results (table 4.3), and only the Derwent at Buttercrambe shows a statistical difference between 5-year periods at the 5% level (Table 4.4).

Table 4.2 : Summary statistics of annual maximum series (AM)

(IH Station No.) Station Name	Period	Length of Record (years)	Years of Data Missing (years)	Mean (m^3s^{-1})	Standard Error (m^3s^{-1})	Median (m^3s^{-1})	Mode (m^3s^{-1})	Standard Deviation (m^3s^{-1})	Min (m^3s^{-1})	Max (m^3s^{-1})
(27001) Nidd @ Hunsingore	1934-1996	63	0	141.83	8.31	120.01	161.48	65.44	61.87	310.93
(27002) Wharfe @ Flint Mill	1936-1996	61	0	249.78	8.59	233.37	203.15	67.12	148.63	417.35
(27007) Ure @ Westwick	1956-1996	41	0	288.35	15.88	269.44	298.30	101.69	169.83	628.57
(27021) Don @ Doncaster	1868-1996	129	16	161.83	6.17	153.46	153.46	65.59	41.02	348.29
(27028) Aire @ Armley	1961-1996	36	1	143.63	5.05	140.02	-	29.87	94.03	211.01
(27041) Derwent @ Buttercrambe	1962-1996	35	0	89.03	4.37	81.60	-	25.85	52.27	159.00
(27071) Swale @ Crakehill	1955-1996	42	0	177.69	5.32	182.02	-	34.51	94.00	259.34
Aire & Calder at Castleford *	1864-1968	105	3	4.64	0.04	4.74	5.03	0.37	3.91	5.56
Calder at Broardreach	1863-1968	106	5	400.91	17.49	360.00	460.00	175.81	84.00	1020.00
Ouse at Viking *	1880-1996	117	0	8.53	0.06	8.54	7.88	0.61	6.96	10.12

* Stage record (mAOD)

Table 4.3 : Runs Chart results for annual maximum series (AM)

(IH Station No.) Station Name	No of runs about median	Expected No of runs	Longest run about mean	P-Value for Clustering	P-Value for Mixtures	No of runs up or down	Expected No of runs	Longest run up or down	P-Value for Trends	P-Value for Oscillation
(27001) Nidd @ Hunsingore	34	32.00	5	0.696	0.304	43	41.00	3	0.730	0.271
(27002) Wharfe @ Flint Mill	28	31.49	7	0.184	0.817	41	40.33	3	0.581	0.419
(27007) Ure @ Westwick	17	21.49	7	0.078	0.922	24	27.00	4	0.128	0.872
(27028) Aire @ Armley	15	19.00	6	0.089	0.912	21	23.67	5	0.140	0.860
(27041) Derwent @ Buttercrambe	16	18.49	6	0.197	0.803	27	23.00	4	0.940	0.060
(27071) Swale @ Crakehill	21	22.00	6	0.377	0.623	30	27.67	3	0.809	0.191
Aire & Calder @ Castleford	39	48.50	13	0.026*	0.975	65	63.00	4	0.689	0.311
Calder @ Broadreach	46	47.00	6	0.417	0.583	63	61.00	5	0.691	0.309
Ouse @ Viking	45	58.98	19	0.005**	0.995	77	77.00	4	0.500	0.500

* = Significant at the 5% level

** = Significant at the 0.5% level

(27021) Don @ Doncaster could not be tested due to significant gaps

Table 4.4 : *Average annual maximum flood for 5-year periods. Bold indicates highest average value, italics denote lowest average value for each site. Units in cumecs unless otherwise stated.* * Stage record (m AOD). ** Significant at the 5% level.

5-year Period	27001 - Nidd	27002 - Wharfe	27007 - Ure	27021 - Don	27028 - Aire	27041 - Derwent	27071 - Swale	Aire & Calder-Castleford *	Calder - Broadreach	Ouse - York *
1862-1866	-	-	-		-	-	-	4.63	412.00	-
1867-1871	-	-	-	**247.48**	-	-	-	4.91	497.40	-
1872-1876	-	-	-	195.14	-	-	-	4.87	No data	-
1877-1881	-	-	-	178.39	-	-	-	4.91	624.00	8.99
1882-1886	-	-	-	207.67	-	-	-	4.78	479.40	8.53
1887-1891	-	-	-	182.67	-	-	-	4.86	**603.80**	8.44
1892-1896	-	-	-	228.05	-	-	-	4.96	369.00	8.62
1897-1901	-	-	-	155.11	-	-	-	4.55	391.00	8.31
1902-1906	-	-	-	110.20	-	-	-	*4.26*	362.80	*7.77*
1907-1911	-	-	-	165.85	-	-	-	4.40	432.40	8.12
1912-1916	-	-	-	111.52	-	-	-	4.33	420.80	8.11
1917-1921	-	-	-	163.37	-	-	-	4.68	508.20	7.97
1922-1926	-	-	-	149.85	-	-	-	4.60	391.00	8.46
1927-1931	-	-	-	225.41	-	-	-	4.72	355.00	8.66
1932-1936	133.93	-	-	192.17	-	-	-	4.44	313.00	8.32
1937-1941	125.81	263.44	-	201.04	-	-	-	4.62	354.40	8.51
1942-1946	136.85	258.37	-	161.41	-	-	-	4.77	365.40	8.61
1947-1951	140.90	**290.40**	-	*109.04*	-	-	-	4.51	292.00	9.04
1952-1956	106.24	204.43	-	122.34	-	-	148.11	4.31	276.60	8.05
1957-1961	106.15	222.50	271.22	131.18	-	-	171.79	4.64	285.60	8.70
1962-1966	137.36	270.66	292.34	156.15	142.66	93.96	187.61	4.72	*275.40*	8.86
1967-1971	183.94	263.62	291.48	164.83	152.04	**121.70**	184.96	**5.13**	429.00	8.59
1972-1976	*97.70*	*201.19*	*224.82*	123.89	*120.05*	71.26	*137.71*	No data	No data	8.22
1977-1981	157.07	252.73	268.76	170.30	153.41	113.87	184.52	No data	No data	**9.23**
1982-1986	165.17	264.44	320.46	159.98	**165.67**	76.80	193.04	No data	No data	9.14
1987-1991	146.89	228.60	324.63	138.43	131.55	*67.24*	175.60	No data	No data	8.82
1992-1996	**217.87**	248.15	**335.67**	165.40	145.66	78.38	**198.11**	No data	No data	9.07
Kruskall-Wallis Test P-value	0.323	0.410	0.213	0.117	0.218	0.002**	0.110	0.000**	0.000**	0.002**

Figure 4.5 : Annual maximum series (AM)

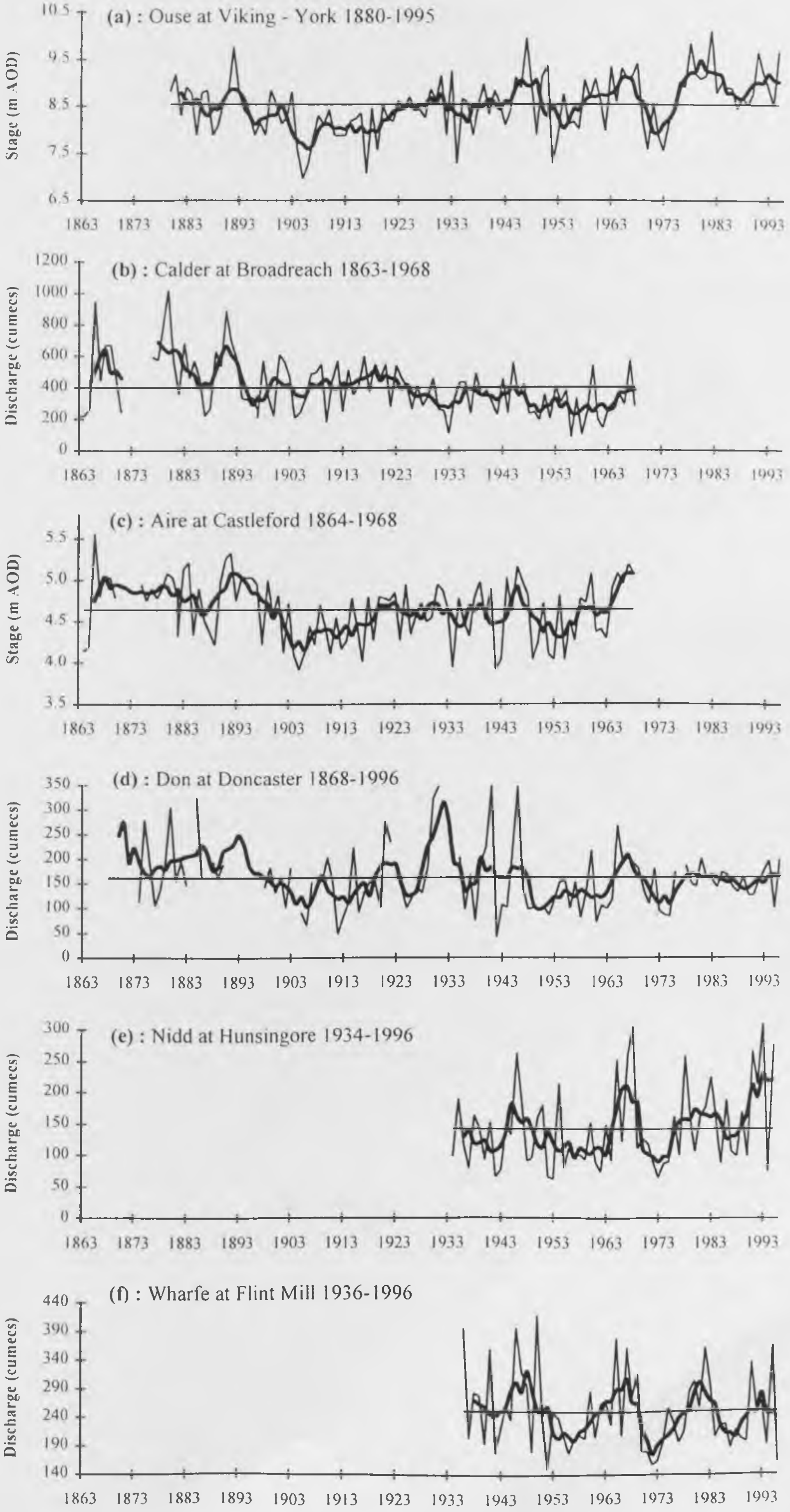
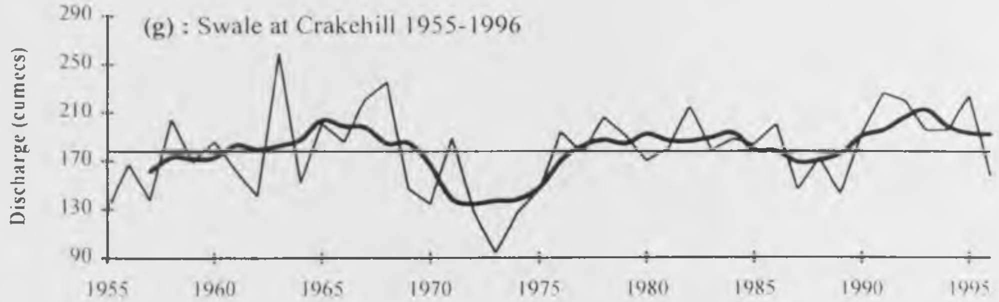
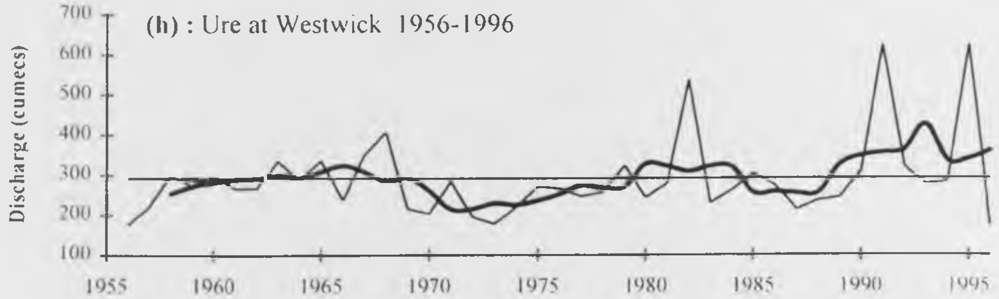
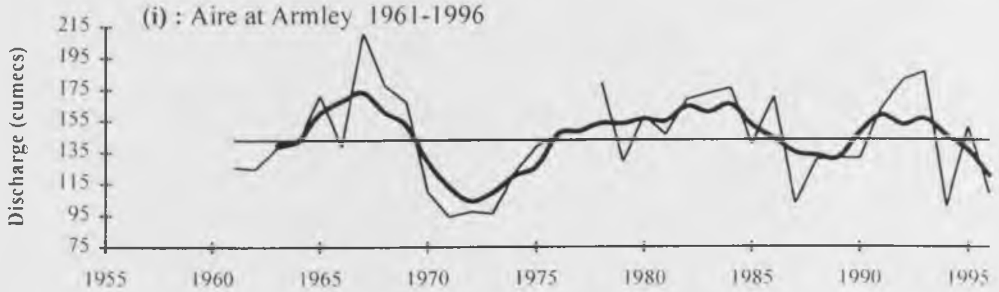
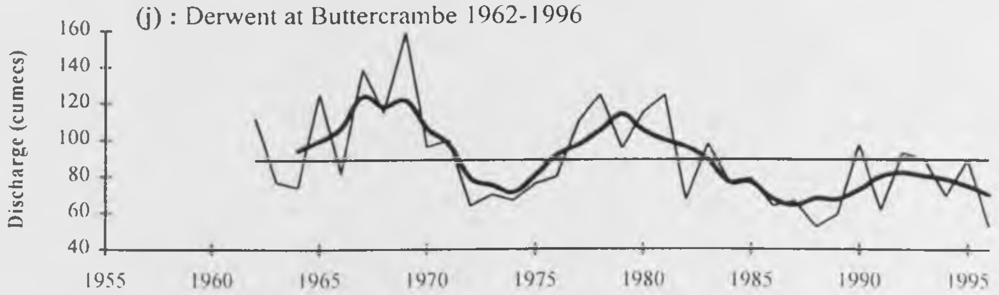


Figure 4.5 : Annual maximum series (con't)


(g) : Swale at Crakehill 1955-1996


(h) : Ure at Westwick 1956-1996


(i) : Aire at Armley 1961-1996


(j) : Derwent at Buttercrambe 1962-1996

Summary chronology - annual maximum (AM) series

Analysis of AM series at ten different sites in the Ouse basin, over the period 1863-1996, has revealed several distinct periods characterised by similar flood magnitudes. Over the period *ca.* 1865-1900, evidence from four major lowland tributaries show a phase of high flood magnitudes, particularly on the Don, Aire and Calder. This was followed by a rapid decline in flood magnitudes over the period *ca.* 1900-1920, which is particularly evident on the Ouse at York and the Aire and Calder at Castleford. This decline is also visible in the Don at Doncaster record, although there were several relatively large floods during this period. On the Calder at Broadreach this marked decline in flood magnitude is also clear, but unlike the other sites flood magnitudes continued to decline after this period until the end of the record in 1968. In general, flood magnitudes increased to a peak around 1930 on the Ouse and Don, and to a lesser extent on the Aire and Calder at Castleford. From the 1930s onwards there appears to have been a series of peaks and troughs in flood magnitude, synchronous throughout the Ouse basin, with the exception of the Calder at Broadreach. Periods of high flood magnitudes occurred in the mid-1940s, mid-1960s, late-1970s to early-1980s, and in the 1990s. The only exception was the Derwent at Buttercrambe where magnitude has decreased in the 1990s. Indeed, this most recent period (1992-1996) has shown the highest 5-year average AM values for most of the northern Yorkshire Ouse (Swale, Ure, Nidd). Low flood magnitudes occurred in the 1950s, 1970s and the mid-1980s, with the period 1972-1976 showing the lowest average magnitudes on the Swale, Nidd, Ure, Wharfe and Aire (at Armley).

4.2.4.3. Annual mean exceedance (AME)

Eight POT records have been compiled and AME data calculated, summary statistics for these sites are shown in table 4.5. POT data were not available for the Aire and Calder at Castleford or the Calder at Broadreach, and therefore only two sites, the Don at Doncaster (1868-1996) and the Ouse at York (1878-1996) extend back to the nineteenth century. On the Don at Doncaster there is a significant gap in the data between 1932 and 1960.

Run Chart results for AME series are summarised in table 4.6 and show that all but one of the records, the Ure at Westwick, are random. The Run Chart results for the Ure suggest the non-random element to be a significant trend within the record. 5-year averages are given in table 4.7 and agree closely with the AM records. The period 1972-1976 showing the lowest average exceedance at six of the sites, and 1992-1996 showing some of the highest averages, particularly in the northern rivers, such as the Ure, Swale and Nidd.

Table 4.5 : Summary statistics of annual mean exccedance (AME)

(IH Station No.) Station Name	Period	Standard Threshold (cumecs)	No of Floods in Record	Length of Record (years)	Years of Data Missing (years)	Mean (m^3s^{-1})	Standard Error (m^3s^{-1})	Median (m^3s^{-1})	Standard Deviation (m^3s^{-1})	Qmax (m^3s^{-1})
(27001) Nidd @ Hunsingore	1934-1996	66.50	242	63	0	29.19	2.53	27.82	20.04	63.00
(27002) Wharfe @ Flint Mill	1936-1996	163.00	218	61	0	45.89	4.44	40.15	34.70	230.97
(27007) Ure @ Westwick	1956-1996	168.70	170	41	0	53.76	4.96	48.79	31.77	152.24
(27021) Don @ Doncaster	1868-1996	112.60	165	129	28	39.17	4.50	25.88	45.47	234.17
(27028) Aire @ Armley	1961-1996	98.40	123	36	0	23.59	2.31	25.13	13.88	51.47
(27041) Derwent @ Buttercrambe	1962-1996	58.70	120	35	0	15.86	1.73	14.72	10.24	34.05
(27071) Swale @ Crakehill	1955-1996	124.50	172	42	0	27.63	2.28	26.19	14.75	59.38
Ouse at Viking*	1880-1996	8.03	253	117	0	0.36	0.03	0.34	0.31	1.73

* Stage Record (m AOD)

Table 4.6 : Run Chart results for annual mean exceedance (AME)

(IH Station No.) Station Name	No of runs about median	Expected No of runs	Longest run about mean	P-Value for Clustering	P-Value for Mixtures	No of runs up or down	Expected No of runs	Longest run up or down	P-Value for Trends	P-Value for Oscillation
(27001) Nidd @ Hunsingore	32	32.49	8	0.450	0.550	45	41.67	3	0.844	0.156
(27002) Wharfe @ Flint Mill	26	31.50	6	0.078	0.922	43	40.33	5	0.795	0.205
(27007) Ure @ Westwick	21	21.50	4	0.439	0.561	22	27.00	3	0.029*	0.971
(27028) Aire @ Armley	21	19.00	6	0.750	0.250	24	23.67	5	0.554	0.446
(27041) Derwent @ Buttercrambe	15	18.50	8	0.116	0.884	23	23.00	4	0.500	0.500
(27071) Swale @ Crakehill	20	22.00	6	0.266	0.734	28	27.67	4	0.550	0.450
Ouse @ Viking	54	60.50	12	0.116	0.884	81	79.00	4	0.669	0.331

* = Significant at the 5% level

(27021) Don @ Doncaster could not be tested due to significant gaps

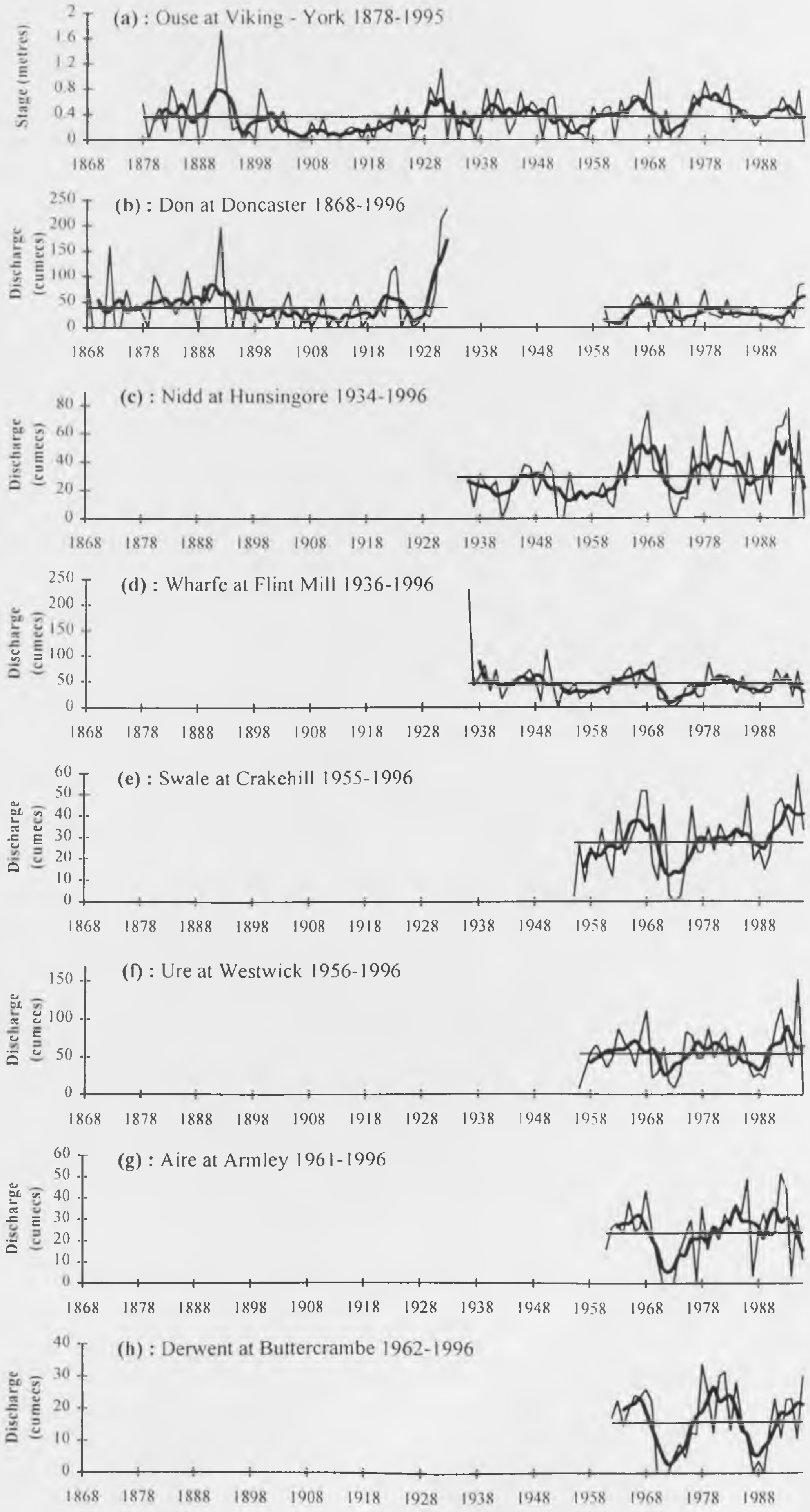
Table 4.7 *: Average annual mean exceedance for standard 5-year periods. Bold indicates highest average value, italics denote lowest average value for each site. Units in cumecs unless otherwise stated.*

5-year Period	(27001)- Nidd	(27002)- Wharfe	(27007)- Ure	(27021)- Don	(27028)- Aire	(27041)- Derwent	(27071)- Swale	Ouse- York *
1872-1876				54.24				
1877-1881				50.29				0.36
1882-1886				53.30				0.42
1887-1891				52.00				0.43
1892-1896				54.34				0.57
1897-1901				37.98				0.31
1902-1906				22.22				0.14
1907-1911				25.15				0.14
1912-1916				24.61				*0.10*
1917-1921				19.78				0.16
1922-1926				51.75				0.28
1927-1931				**67.75**				0.58
1932-1936	30.10			No data				0.28
1937-1941	22.23	57.13		No data				0.45
1942-1946	20.94	44.05		No data				0.40
1947-1951	30.71	**59.23**		No data				0.48
1952-1956	*12.50*	25.56		No data			14.52	0.11
1957-1961	16.54	29.51	47.41	21.71	15.87		21.39	0.37
1962-1966	31.25	56.44	59.66	21.46	28.08	19.87	27.69	0.46
1967-1971	**50.54**	52.23	60.09	39.97	21.32	14.51	35.16	0.41
1972-1976	17.69	*19.03*	42.18	*13.47*	*13.36*	*6.29*	*13.72*	0.24
1977-1981	34.90	44.70	60.14	35.04	19.42	**22.78**	27.89	**0.65**
1982-1986	39.58	46.71	56.03	28.77	**35.24**	20.02	33.54	0.50
1987-1991	31.49	37.37	*41.89*	22.95	21.05	8.14	24.80	0.38
1992-1996	41.37	41.64	**72.09**	46.80	28.21	19.40	**42.06**	0.45
Kruskall-Wallis p-value	0.125	0.178	0.683	0.610	0.186	0.086	0.105	0.139

P-value must be lower than 0.05 to be significant at the 5% level

** Stage record (m AOD)*

Figure 4.6 : Annual mean exceedance series (AME)



The timing of major changes in flood magnitude from AME records are similar to those identified in the AM series and are shown in figure 4.6. The late nineteenth century, late-1920s, mid-1940s, mid-to-late 1960s, mid-1970s to mid-1980s, and the 1990s were periods of high flood magnitude. Low flood magnitudes are evident in the early part of the twentieth century until around 1920, and in the 1930s, 1950s, early-to-mid 1970s, and the mid-to-late 1980s.

There are two notable variations in the AME and AM diagrams. Firstly, on the Derwent at Buttercrambe, the AM record suggests that magnitudes have declined in the 1990s, whereas the AME record shows magnitude to be increasing. This would indicate that maximum flood discharges are declining, but the frequency of more moderate flood events has increased. Secondly, the AM record for the Ure at Westwick shows three very large flood peaks in 1982, 1991 and 1995, these peaks have been 'smoothed' by the AME approach, whilst still preserving the overall trends common to both series.

AM and AME series both show temporal variations in flood magnitude, AM data represent the maximum peak per year, whereas AME data represent the average annual exceedance over a standard threshold. Comparison of the two series show that the timing of major changes in flood magnitude are in close agreement. This suggests that it is not always necessary to use both measures of annual magnitude, either will give a clear indication of significant temporal variations in flood magnitude.

4.2.4.4. Annual flood frequency (AFF)

Mean flood frequency values and other summary statistics for each of the eight sites are given in table 4.8, and clearly show shorter flood records tend to have a higher mean annual frequency. This may suggest that flood frequencies may have been higher in the recent period. Run Chart summaries are given in table 4.9, and show that three of the eight flood frequency series are non-random, the Derwent, Don and the Ouse records all exhibiting clustered data points, with the Don also showing evidence of a trend. The remaining series are statistically random.

Annual flood frequency series are shown in figure 4.7. Only two POT records extend back to the nineteenth century, the Ouse at York and the Don at Doncaster. These series show that this early period was characterised by generally low flood frequencies, except between the late-1870s and early-1880s. From the 1880s until the 1940s flood frequencies remained extremely low. There followed a marked increase in flood frequency on the Ouse, Nidd and Wharfe

Table 4.8 : Summary statistics of annual flood frequency(AFF)

(IH Station No.) Station Name	Period	Standard Threshold (cumecs)	No of Floods in Record	Length of Record (years)	Years of Data Missing	Mean (m^3s^{-1})	Standard Error (m^3s^{-1})	Median (m^3s^{-1})	Standard Deviation (m^3s^{-1})	Min (m^3s^{-1})	Max (m^3s^{-1})
(27001) Nidd @ Hunsingore	1934-1996	66.50	242	63	0	3.84	0.31	4.00	2.44	0	10
(27002) Wharfe @ Flint Mill	1936-1996	163.00	218	61	0	3.57	0.26	3.00	2.01	0	8
(27007) Ure @ Westwick	1956-1996	168.70	170	41	0	4.15	0.32	4.00	2.03	1	10
(27021) Don @ Doncaster	1868-1996	112.60	165	129	28	1.62	0.17	1.00	1.70	0	8
(27028) Aire @ Armley	1961-1996	98.40	123	36	0	3.42	0.37	3.00	2.23	0	8
(27041) Derwent @ Buttercrambe	1962-1996	58.70	120	35	0	3.43	0.43	3.00	2.56	0	9
(27071) Swale @ Crakehill	1955-1996	124.50	172	42	0	4.10	0.32	4.00	2.08	0	10
Ouse at Viking*	1880-1996	8.03	253	117	0	2.13	0.17	2.00	1.87	0	9

* Stage Record in mAOD

Table 4.9 : Run Chart results for annual flood frequency

(IH Station No.) Station Name	No of runs about median	Expected No of runs	Longest run about mean	P-Value for Clustering	P-Value for Mixtures	No of runs up or down	Expected No of runs	Longest run up or down	P-Value for Trends	P-Value for Oscillation
(27001) Nidd @ Hunsingore	31	29.00	10	0.717	0.283	44	41.67	5	0.760	0.240
(27002) Wharfe @ Flint Mill	31	31.40	6	0.456	0.544	37	40.33	6	0.152	0.848
(27007) Ure @ Westwick	19	20.51	10	0.307	0.693	30	27.00	3	0.872	0.128
(27028) Aire @ Armley	15	18.80	6	0.098	0.902	21	23.70	6	0.140	0.860
(27041) Derwent @ Buttercrambe	13	17.80	8	0.043*	0.957	22	23	3	0.340	0.660
(27071) Swale @ Crakehill	21	21.20	9	0.470	0.530	26	27.67	3	0.267	0.733
Ouse @ Viking	32	52.00	34	0.000*	1.000	75	79	5	0.190	0.810

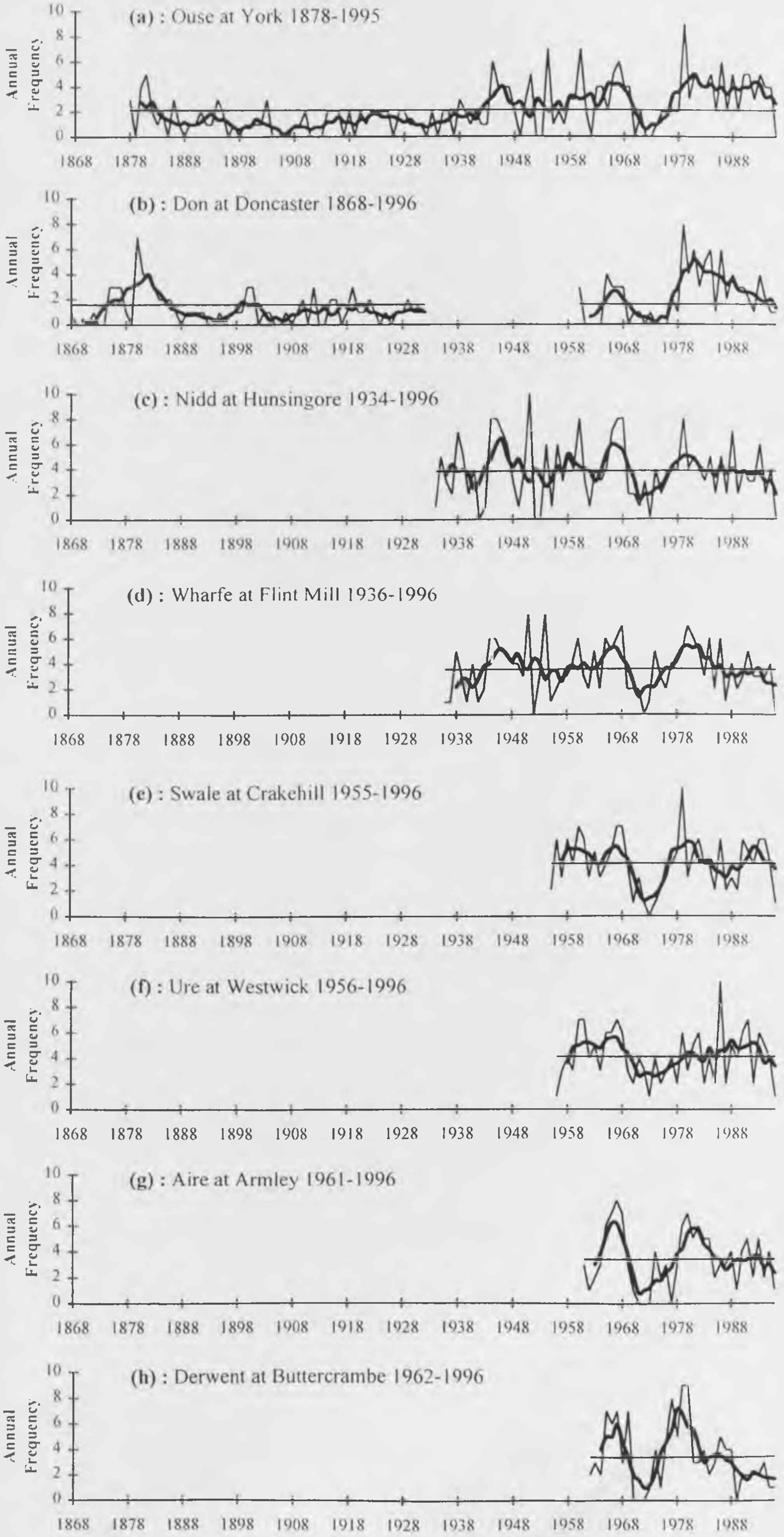
* = Significant at the 5% level
(27021) Don @ Doncaster could not be tested due to significant gaps

Table 4.10 : Average annual flood frequency for standard 5-year periods. Bold indicates highest average value, italics denote lowest average value for each site

5-year Period	**(27001)- Nidd**	**(27002)- Wharfe**	**(27007)- Ure**	**(27021)- Don**	**(27028)- Aire**	**(27041)- Derwent**	**(27071)- Swale**	**Ouse- York**
1872-1876				1.40				
1877-1881				3.00				3.00
1882-1886				2.60				1.60
1887-1891				0.80				1.00
1892-1896				*0.40*				1.40
1897-1901				1.80				*0.80*
1902-1906				*0.40*				*0.80*
1907-1911				0.80				*0.80*
1912-1916				1.40				1.20
1917-1921				1.20				1.00
1922-1926				0.80				1.60
1927-1931				1.20				1.40
1932-1936	3.00			No data				1.20
1937-1941	4.00	2.80		No data				1.60
1942-1946	4.80	4.00		No data				3.20
1947-1951	4.80	4.80		No data				2.80
1952-1956	2.60	2.80		No data			4.00	2.00
1957-1961	4.60	3.80	**4.80**	0.60			5.20	3.20
1962-1966	3.80	4.00	**4.80**	1.40	3.80	4.00	4.00	3.00
1967-1971	4.20	3.80	4.40	1.60	3.80	3.40	4.40	3.20
1972-1976	*2.40*	*2.20*	*2.60*	0.20	*1.80*	*2.20*	*1.60*	1.00
1977-1981	**5.00**	**5.20**	4.00	**4.20**	**4.20**	**6.80**	**5.40**	**4.20**
1982-1986	3.80	4.40	**4.80**	**4.20**	**4.20**	3.40	4.40	**4.20**
1987-1991	3.60	3.00	**4.80**	2.80	3.40	2.40	3.60	3.80
1992-1996	3.00	2.60	3.60	1.80	2.80	1.80	4.20	3.20
Kruskall-Wallis P-value	0.855	0.287	0.405	0.000	0.733	0.092	0.256	0.007

P-value must be lower than 0.05 to be significant at the 5% level

Figure 4.7 : Annual flood frequency series (AFF)



(a) : Ouse at York 1878-1995

(b) : Don at Doncaster 1868-1996

(c) : Nidd at Hunsingore 1934-1996

(d) : Wharfe at Flint Mill 1936-1996

(e) : Swale at Crakehill 1955-1996

(f) : Ure at Westwick 1956-1996

(g) : Aire at Armley 1961-1996

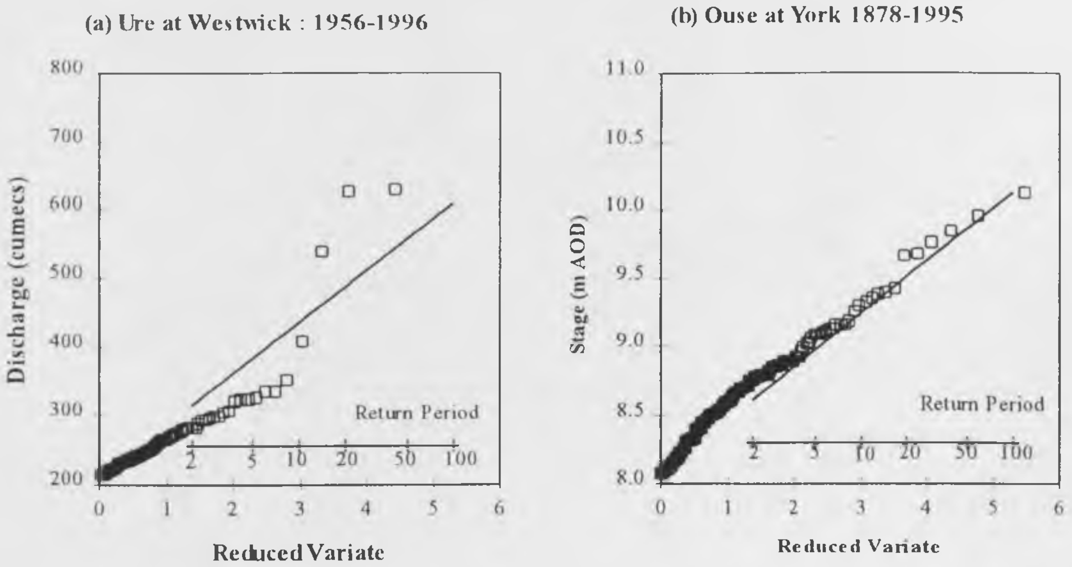
(h) : Derwent at Buttercrambe 1962-1996

around 1944 Unfortunately, the major gap in the Don POT record (1932-1960) occurs over the period when these dramatic changes in flood frequency are evident Large inter-annual variations in the Ouse, Nidd and Wharfe records are evident in the 1950s, with 5-year running means staying close to the long-term average until the mid-1960s when there were several years with high flood frequencies at all sites. From around 1969 to 1977 there was a dramatic decline in flood frequency. Indeed, the 5-year period 1972-1976 (table 4 10), has the lowest recorded flood frequencies at six of the eight sites. After 1977 flood frequencies increased dramatically with the period 1977-1981 showing the highest average frequencies at seven of the eight sites. A relative decline has occurred since the early-1980s through to the present at all sites, however, on the Ouse at York this decline has not been so pronounced.

4.2.4.5. Annual flood frequencies over various thresholds

This technique is used to detect temporal variation in the frequency of floods over a specified magnitude. Each threshold is based on return period estimates using the whole POT record, for Q_2, Q_{10} and Q_{20}, calculated using the POT model outlined in section 4.2.3. This method allows for comparability of flood frequency and magnitude between sites and has the principal advantage of highlighting the timing of extreme events ($>Q_{10}$). A disadvantage of this technique however, occurs when the POT model does not fit the data well (e.g.; the Ure at Westwick - figure 4.8(a)) and return period estimates may be inaccurate.

Figure 4.8 *: Flood frequency curves for (a) the Ure at Westwick and (b) the Ouse at York, showing examples of a poor (a) and a good (b) fit of the POT model*



Similar trends to those already observed are shown clearly when examining floods over the Q_2 (fairly moderate events) threshold in figure 4.9. High frequencies of floods above this threshold occur in the late nineteenth century and decline dramatically in the early part of the twentieth century. Frequencies increase in the 1940s, and show peaks in the 1960s, late-1970s to early-1980s and the 1990s. These patterns confirm those already established from earlier analysis, however a number of interesting variations from these trends are evident at higher magnitudes.

The frequency of floods over higher thresholds are shown for each site in figures 4.10 and 4.11. In general peaks still occur around the dates outlined above, however the 1960s and 1990s appear to have a higher frequency of these high magnitude events, particularly on the northern tributaries. The Don record shows a markedly different trend, with the majority of events $>Q_{10}$ occurring in the late nineteenth century and between 1917 and 1931. The Ouse at York shows

*Figure 4.9 : Annual frequency over Q , threshold for each site. * indicates start of record*

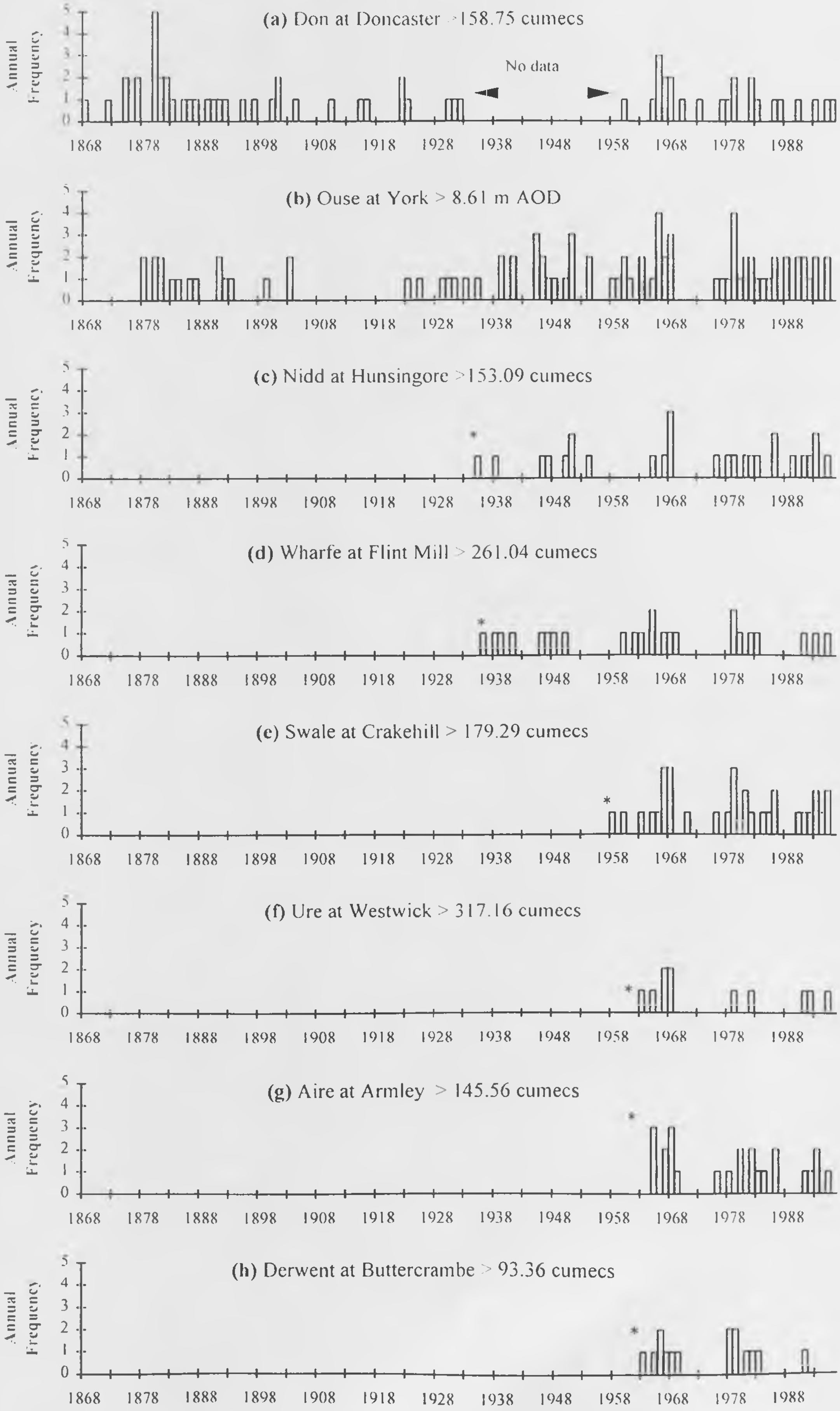


***Figure 4.10** : Annual frequency over Q_{10} threshold for each site. * indicates start of record*

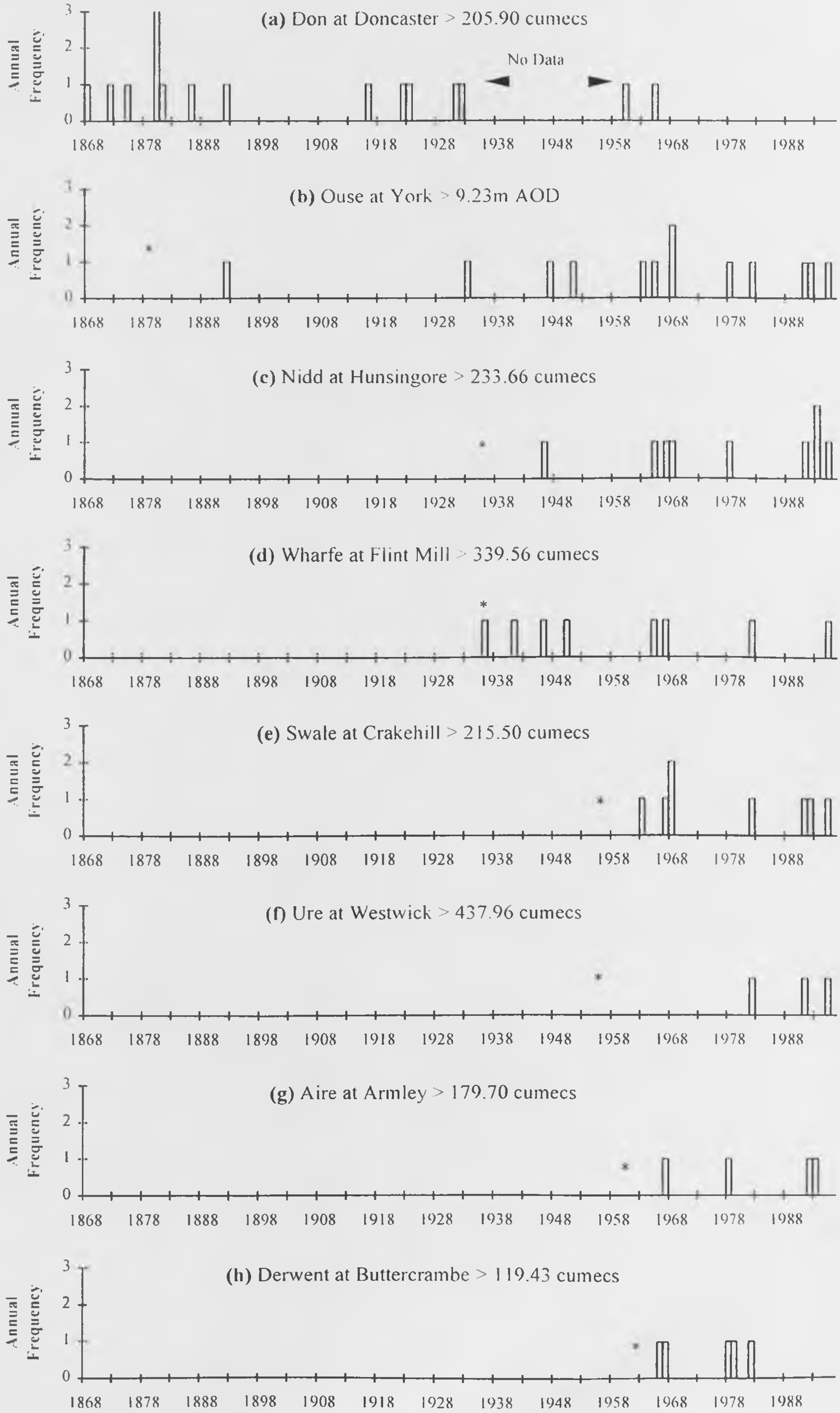
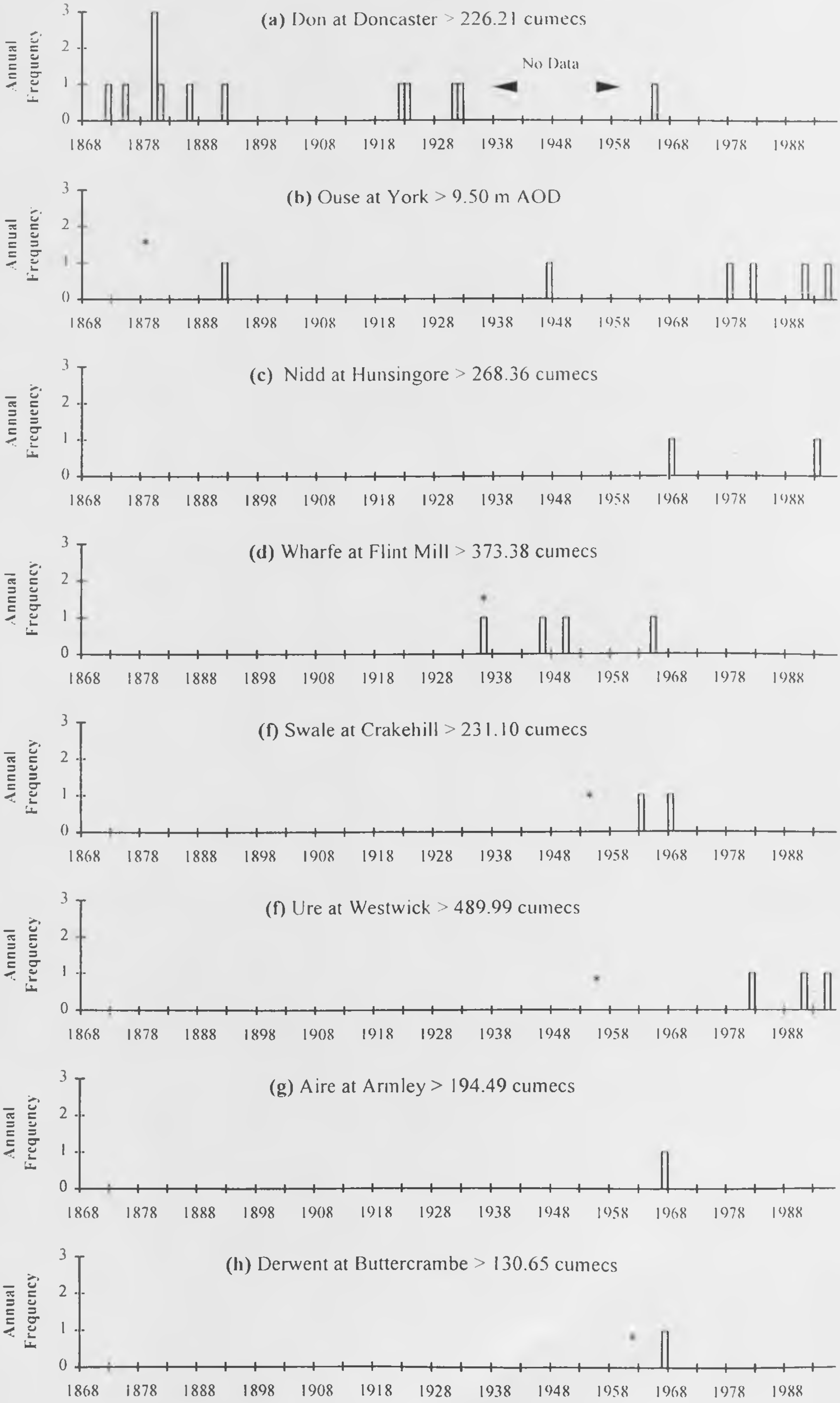


*Figure 4.11 : Annual frequency over Q_{20} threshold for each site * indicates start of record*



(a) Don at Doncaster > 226.21 cumecs

(b) Ouse at York > 9.50 m AOD

(c) Nidd at Hunsingore > 268.36 cumecs

(d) Wharfe at Flint Mill > 373.38 cumecs

(f) Swale at Crakehill > 231.10 cumecs

(f) Ure at Westwick > 489.99 cumecs

(g) Aire at Armley > 194.49 cumecs

(h) Derwent at Buttercrambe > 130.65 cumecs that all but one of the thirteen $>Q_{10}$ events occurred after the 1920s, and four of the six $>Q_{20}$ events have occurred since 1978, suggesting an increase in the highest magnitude events in the most recent period. Some or all of these four large flood events, 1978, 1982, 1991 and 1995, are also evident at Q_{10} or Q_{20} thresholds at all the other sites, however, some of these records are relatively short, and long-term comparisons cannot be made, clearly illustrating that this kind of approach is better when applied to long records of flooding. The two long records that are available show the timing of high magnitude floods to be markedly different.

4.2.4.6. Flood seasonality

Considerable variability in flood seasonality has been noted in the UK by Hewson (Nd) and Black (1992). Such variations may help to explain the observed shifts in flood frequency and magnitude in the Ouse basin, and also help to build a general picture of the flood characteristics of the area. Several techniques have been used in this study to investigate flood seasonality, the percentage frequency of POT floods in two-monthly periods (Dec-Jan, Feb-Mar etc.), POT and AM day of flood diagrams (after May 31st), annual frequency of flooding in standard seasons (e.g. winter = Dec-Jan), and Q-T relationships for individual seasons. The majority of this section uses POT records since this includes all floods over the specified threshold, rather than simply one event per year, as in the AM series.

2-monthly flood frequencies

The percentage of floods that have occurred in two monthly periods, over the entire POT record for each site are shown in figure 4.12. These diagrams indicate that the dominant period of flooding occurs between December-January at all sites, followed by February-March and October-November respectively. The Derwent at Buttercrambe shows February-March to be a much more important POT flood period than any of the other sites. All the other sites have their headwaters in Pennine regions, whereas the Derwent headwaters are in a much more easterly location in the North Yorkshire Moors. Black (1992) quotes work by Hewson (Nd) which concluded that peak flows tend to occur later in the year on eastern draining catchments.

Temporal variation in flood seasonality

Figure 4.13 shows the day of the AM flood with day zero being June 1st of each year. 5-year running means are also plotted to highlight long-term variability. For ease of site comparability figures 4.13 (a)-(d) and (e)-(g) are plotted on different timescales dependant on the length of record The time of year of the AM flood varies considerably with often large inter-annual variation. This leads to a complex overall pattern in the timing of flood peaks, although some common trends are evident particularly after the 1950s when more records are

Figure 4.12 *2-monthly flood frequency percentages over entire period of POT record*
JJ= Jun-Jul, AS - Aug-Sep, ON=Oct-Nov, DJ=Dec-Jan, FM=Feb-Mar, AM=Apr-May

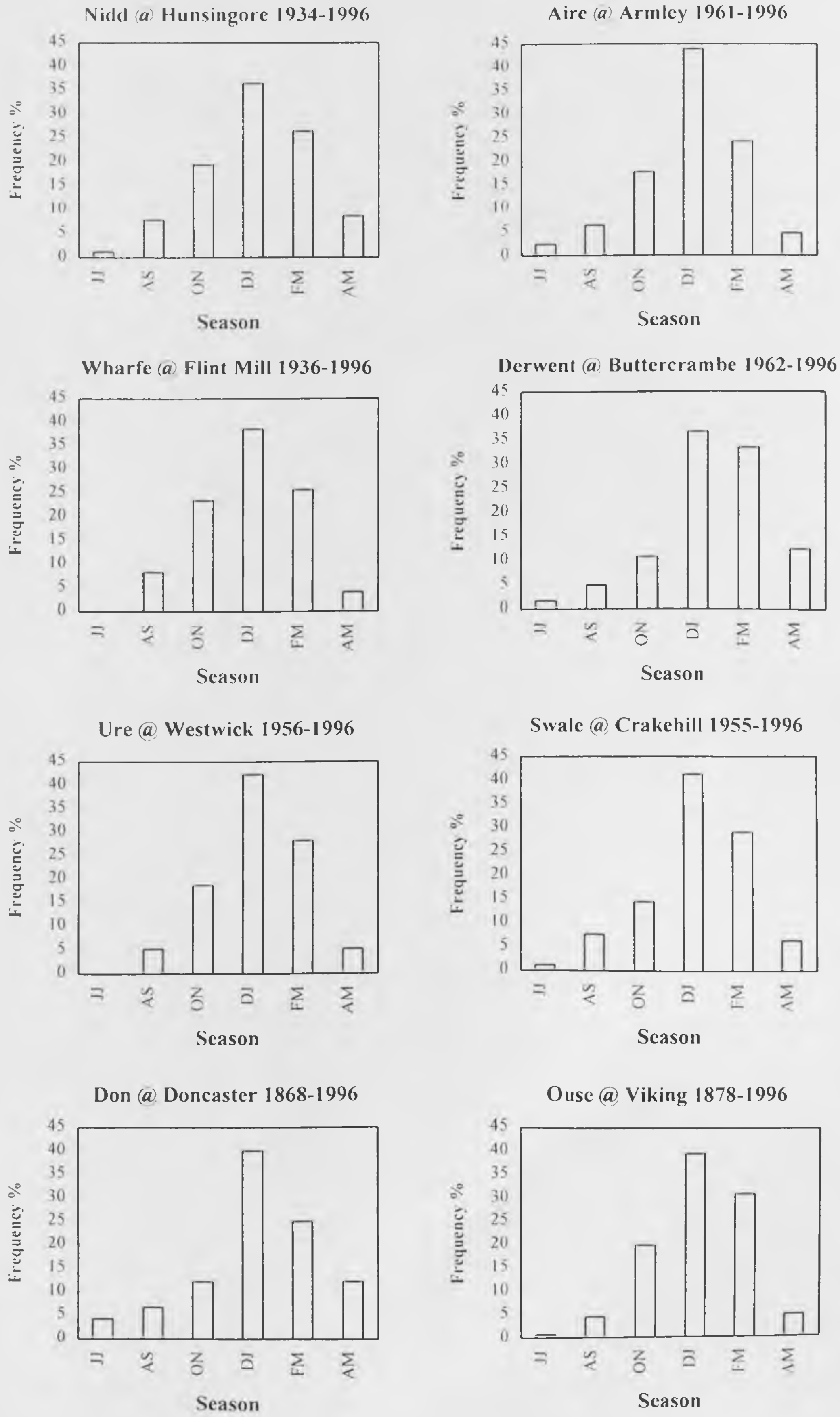
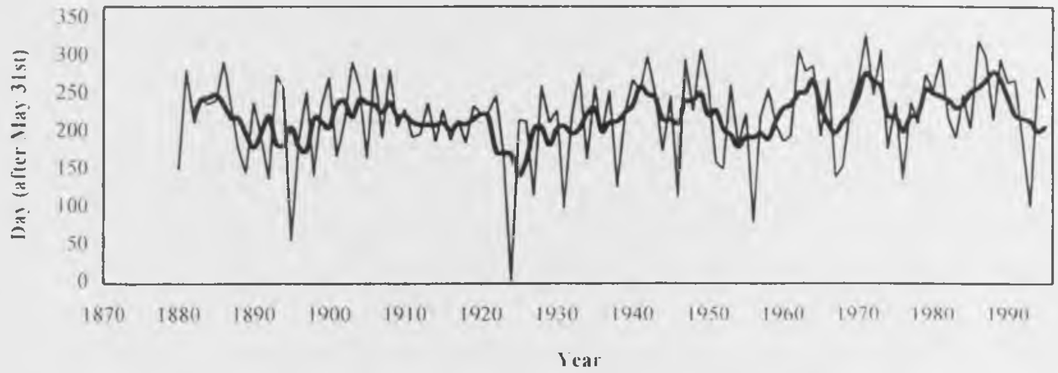
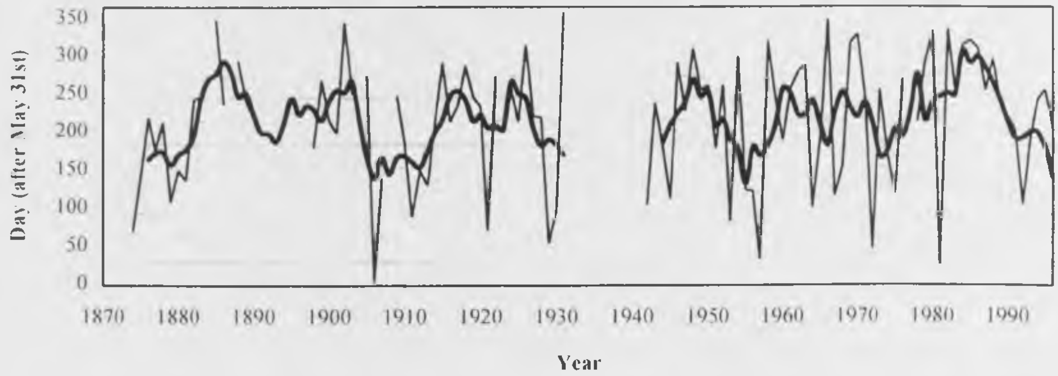


Figure 4.13 : Day of annual maximum (AM) flood (after May 31st)

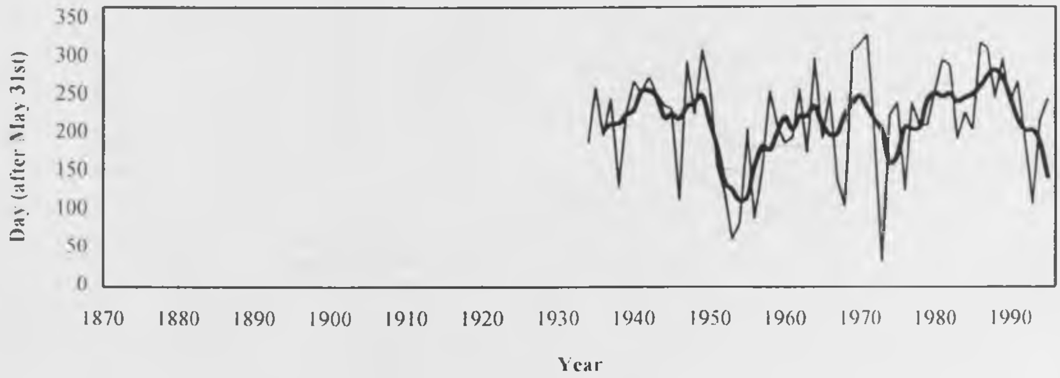
(a) : Ouse at Viking - York 1880-1995



(b) : Don at Doncaster 1874-1996



(c) : Nidd at Hunsingore 1934-1996



(d) : Wharfe at Flint Mill 1936-1996

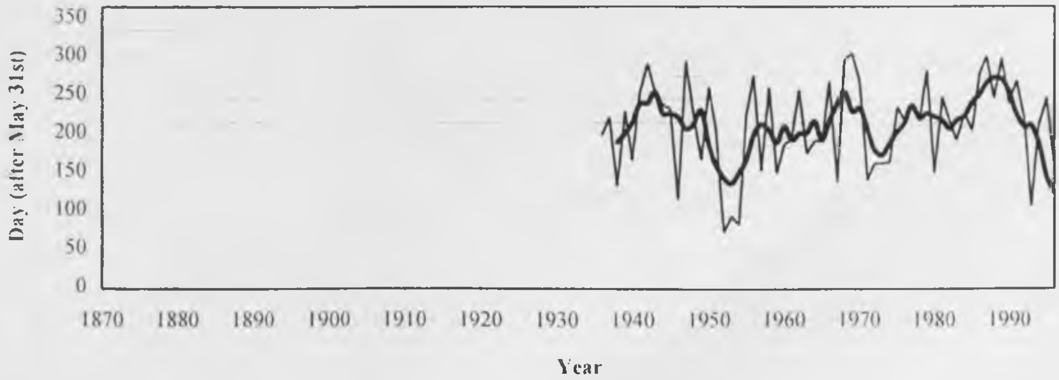
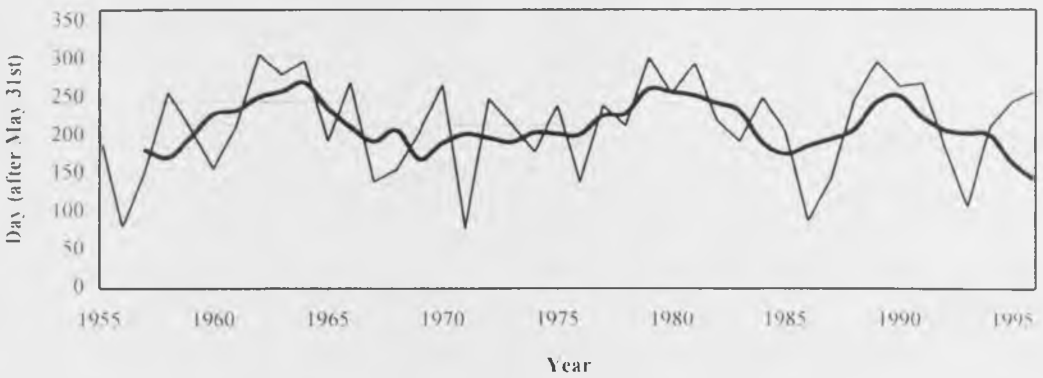
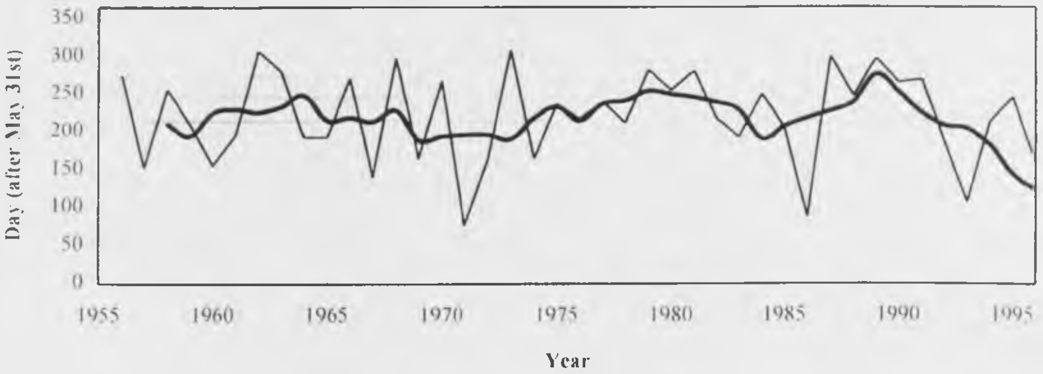


Figure 4.13 : Day of annual maximum (AM) flood (after May 31st) (Con't)

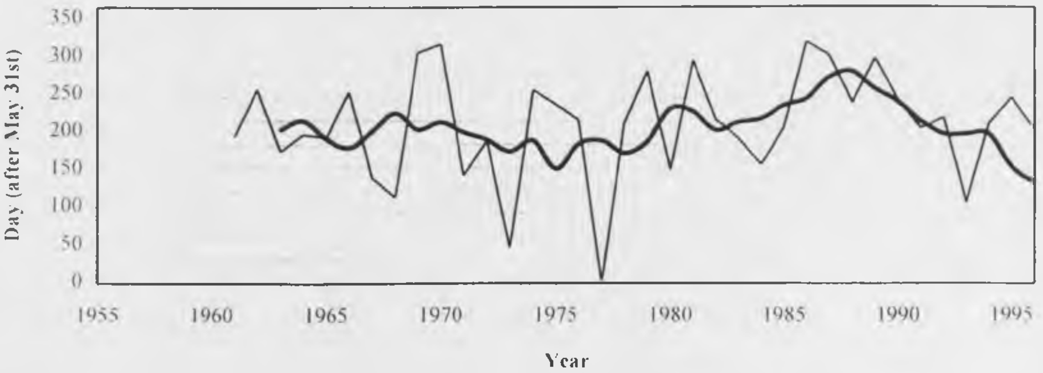
(e) : Swale at Crakehill 1955-1996



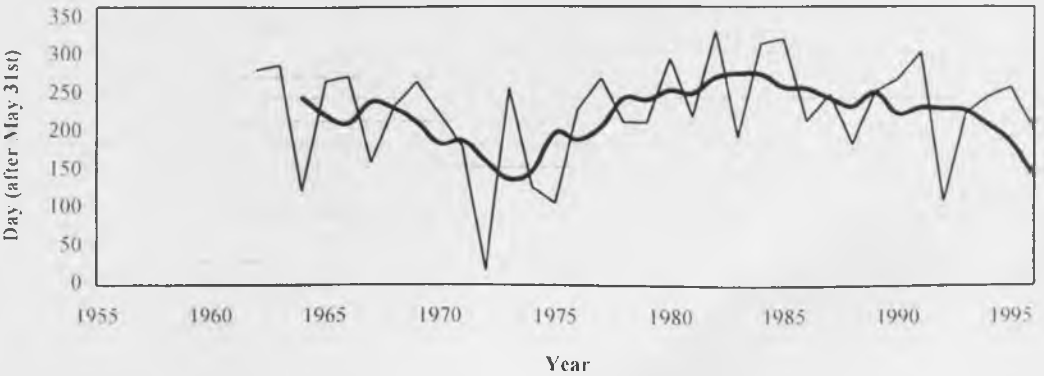
(f) : Ure at Westwick 1956-1996



(g) : Aire at Armley 1961-1996



(g) : Derwent at Buttercrambe 1962-1996



available Floods tended to occur earlier in the year in the 1950s and early-1970s, and later in the year in the mid-1960s and mid-1980s. These periods appear to be in phase with flood magnitude changes, for example in the early-mid 1970s, when flood magnitudes were particularly low throughout the basin it appears that annual maxima tended to occur on average, earlier in the year than higher magnitude events such as those in the 1960s, that occurred in December-February. This may be a product of snowmelt influence and wetter antecedent catchment conditions, which will have a greater influence in the later winter months. The Ouse at York in particular, shows a strong link between flood magnitude and the time of peak flood. However this relationship is not clear cut, the timing of magnitude changes and the time of year of the flood events are not always in phase. The two long records on the Ouse and Don, show marked variations in the day of AM flood particularly in the late nineteenth century, which given the differences already established is not surprising, although since the Don record is incomplete interpretation becomes less reliable.

Diagrams of the annual frequency of POT floods in standard seasons have been produced and are shown in figures 4.14 - 4.17. These diagrams confirm that winter (December-February) (figure 4.14) is the dominant flood season, although there are a number of significant variations through time. Increasing frequencies of spring (March-May) (figure 4.15) floods are often associated with periods of increased flood magnitude, distinct clusters of spring flood events are evident in the late-1940s, mid-late-1960s, and in particular since the mid-late-1970s. This confirms the findings based on AM data, that periods of higher magnitude flooding are occurring in association with an increased frequency of floods later in the year. Furthermore, from evidence in the longer flood records, it appears that the frequency of autumn (September-November) (figure 4.17) flooding has declined significantly since the 1960s. This decline coincides with a relative increase in the incidence of spring floods. Finally, in general, when flood frequencies are high, POT events are common in all seasons, and not restricted to a winter regime.

Flood frequency analysis and seasonality

Black (1992) used flood frequency analysis to investigate seasonality by determining the frequency-magnitude relationships for different seasons on a large number of Scottish rivers. In this case, the POT model is applied for two monthly periods at each site which have at least ten events over the whole period of record. An EXCEL macro was used to calculate the discharge of the Q_{100} event for each season, the Q_{100}/Q_5 growth factor (table 4.11) and Q-T diagrams (appendix A), as described in section 4.2.3.

Figure 4.14 : Annual frequency of ***Winter*** *(December - February) POT floods. * Start of record*

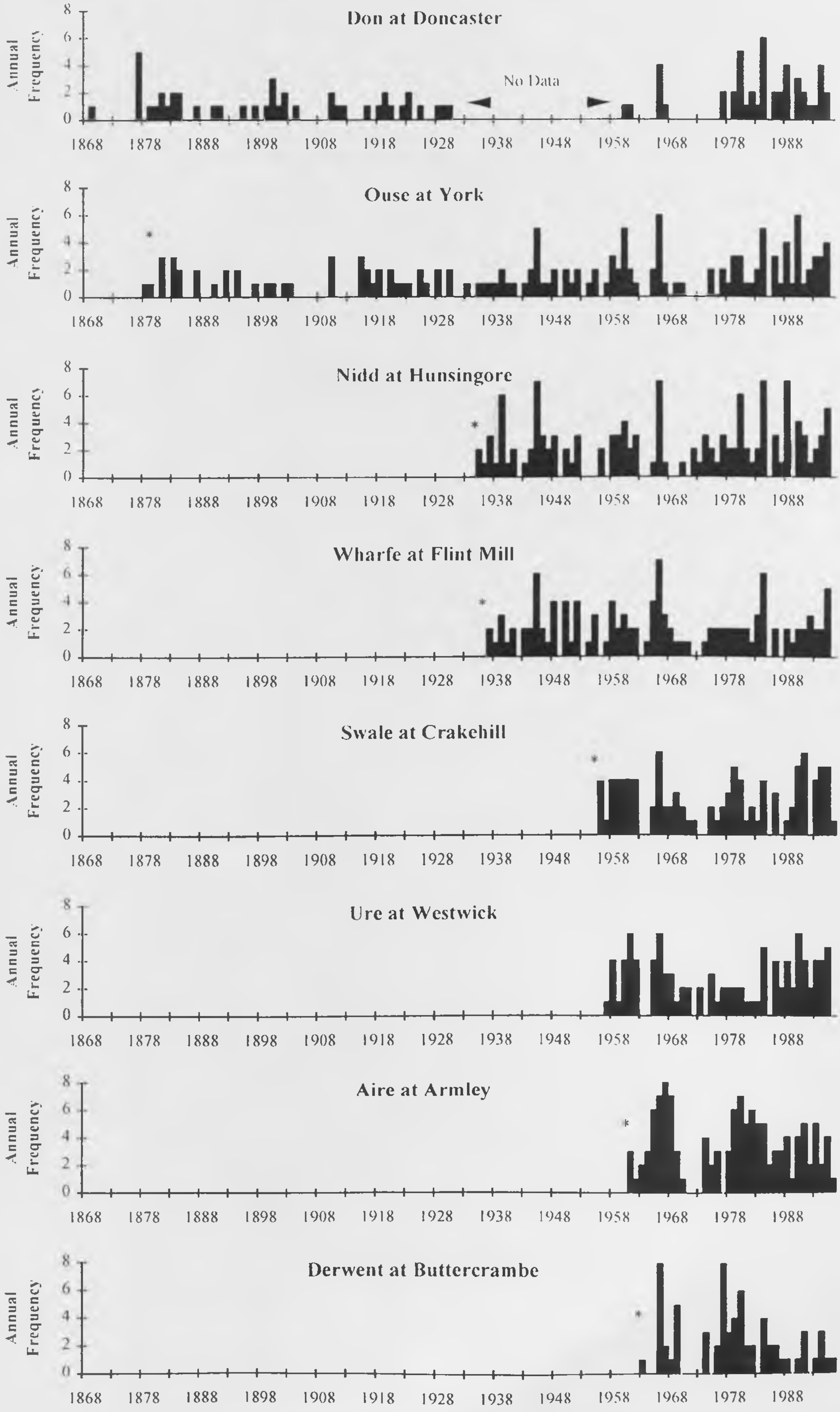


*Figure 4.15 : Annual frequency of **Spring** (March - May) POT floods. * Start of record*

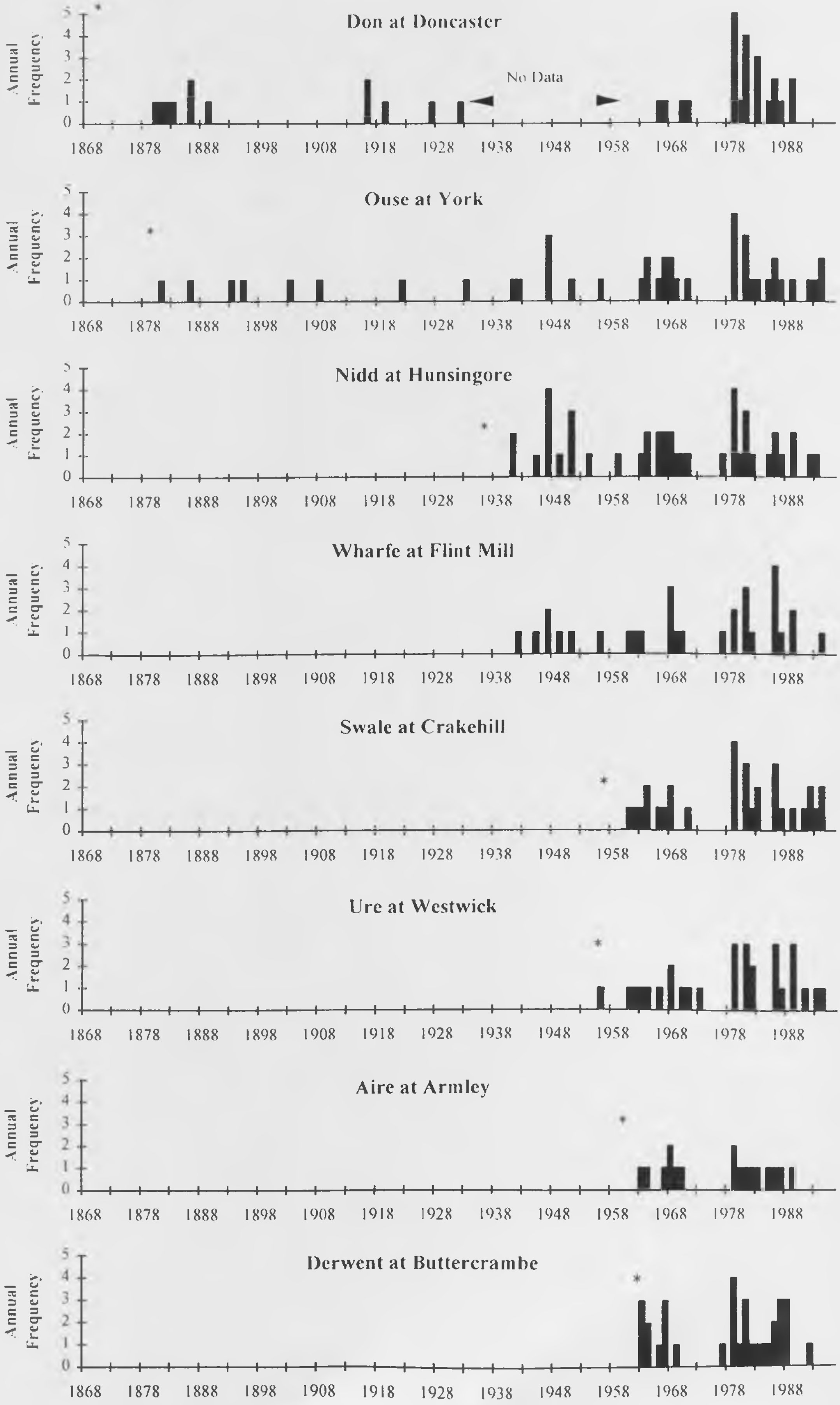


Figure 4.16 : Annual frequency of ***Summer*** *(June - August) POT floods * Start of record*

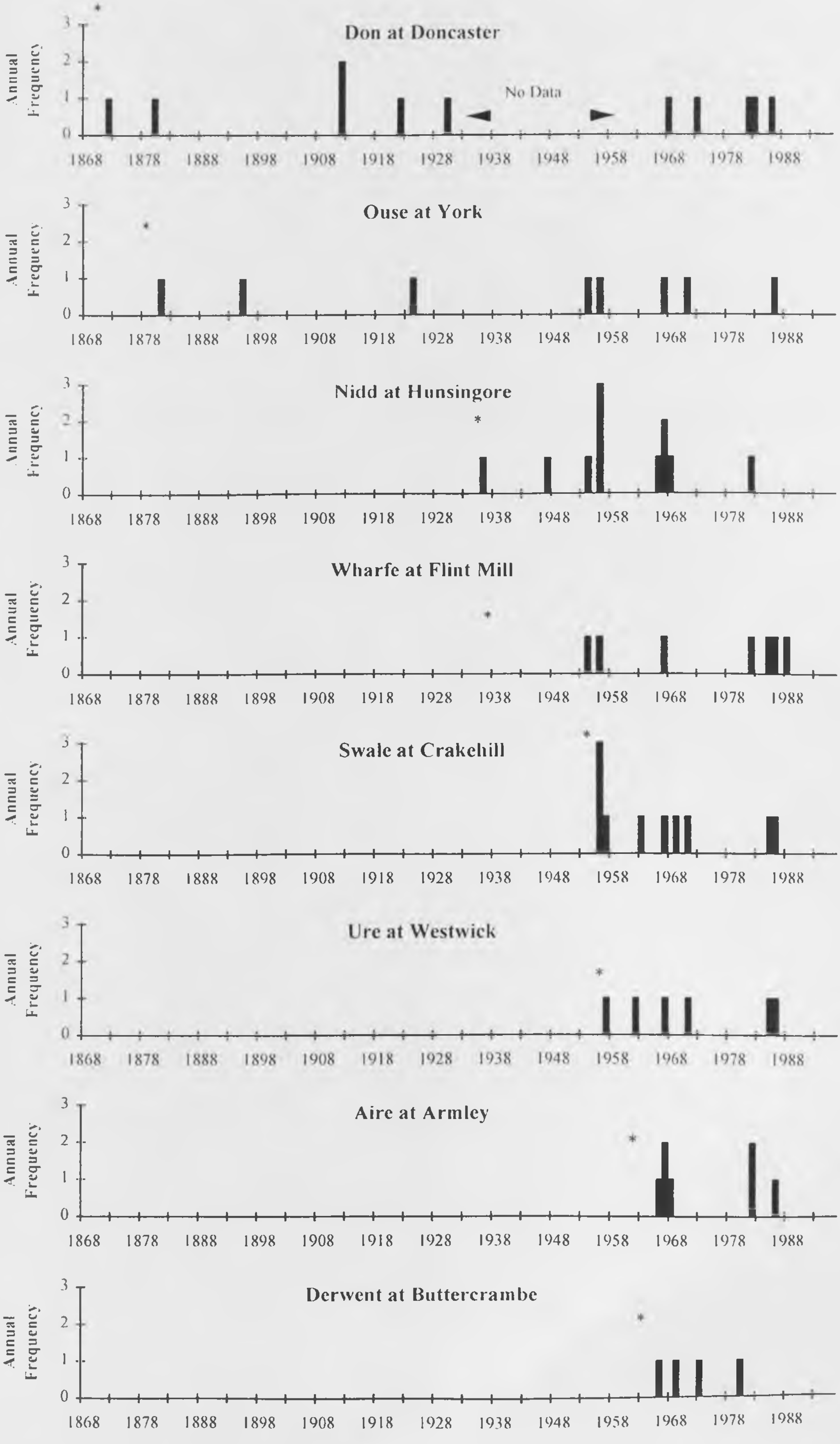


*Figure 4.17 : Annual frequency of **Autumn** (September - November) POT floods * Start of record*

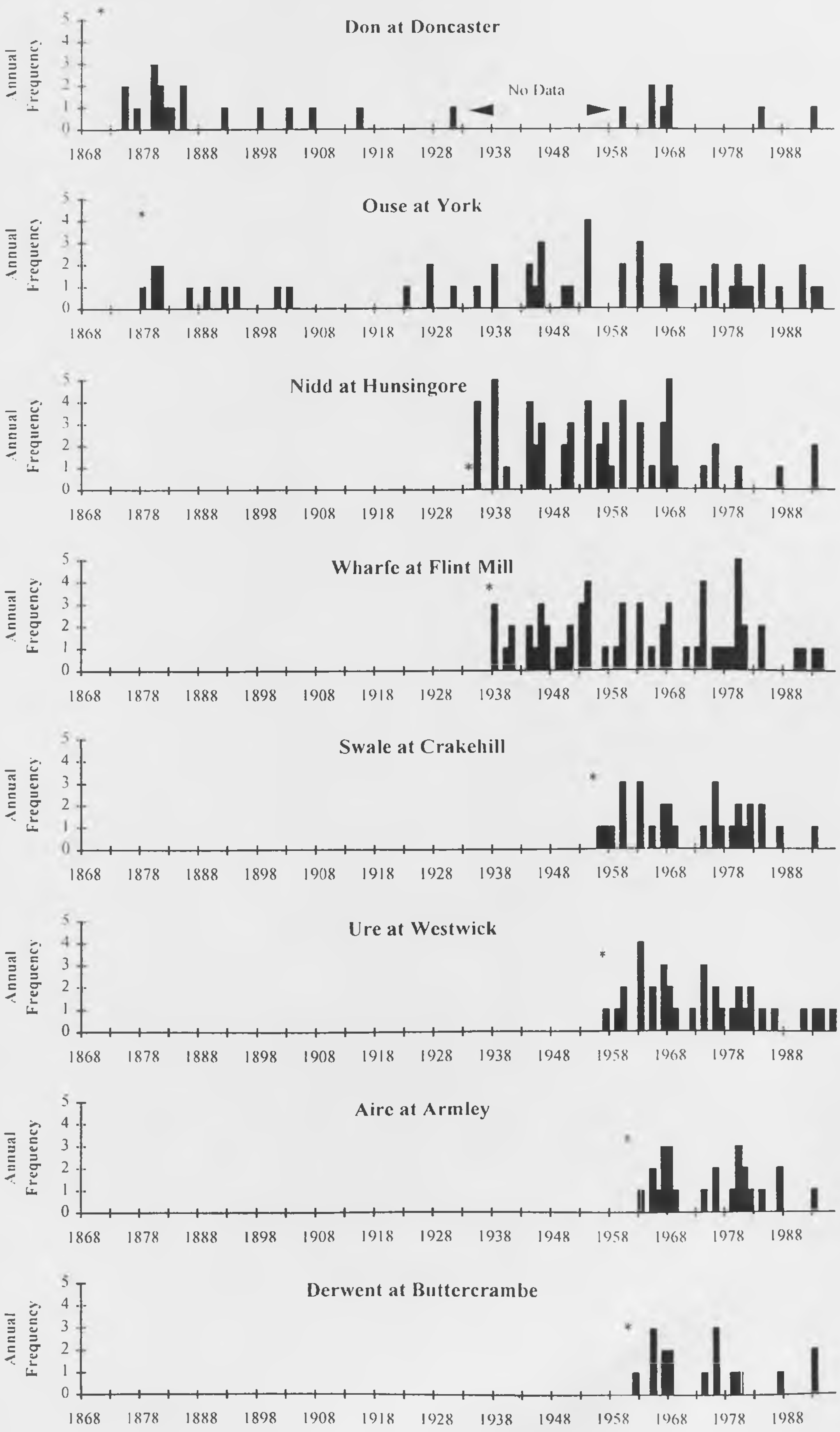


Table 4.11 *Discharge of Q_{100} flood and growth factors Q_{100}/Q_5 for each site (POT). All discharges in m^3s^{-1} unless otherwise stated. Highest Q_{100} estimate for each site shown in bold.*

(a) *: Ouse at the Viking Hotel - York 1878-1995 *stage record (m AOD)*

Season	**Q_{100}**	**Q_5**	**Growth Factor Q_{100}/Q_5**
Jun-Jul	-	-	-
Aug-Sep	8.82	7.78	1.134
Oct-Nov	9.48	8.31	1.140
Dec-Jan	9.72	8.58	1.133
Feb-Mar	**9.81**	8.53	1.149
Apr-May	8.63	7.85	1.010

(b) *: Nidd at Hunsingore 1934-1996*

Season	**Q_{100}**	**Q_5**	**Growth Factor Q_{100}/Q_5**
Jun-Jul	-	-	-
Aug-Sep	**346.67**	97.46	3.557
Oct-Nov	240.15	119.46	2.010
Dec-Jan	266.82	145.06	1.839
Feb-Mar	227.20	123.00	1.847
Apr-May	187.13	87.51	2.138

(c) *: Wharfe at Flint Mill 1936-1996*

Season	**Q_{100}**	**Q_5**	**Growth Factor Q_{100}/Q_5**
Jun-Jul	-	-	-
Aug-Sep	360.18	182.87	1.970
Oct-Nov	334.97	218.63	1.532
Dec-Jan	386.60	250.35	1.544
Feb-Mar	**416.07**	251.32	1.656
Apr-May	-	-	-

(d) *: Aire at Armley 1961-1996*

Season	**Q_{100}**	**Q_5**	**Growth Factor Q_{100}/Q_5**
Jun-Jul	-	-	-
Aug-Sep	-	-	-
Oct-Nov	**218.92**	130.15	1.682
Dec-Jan	214.32	145.66	1.471
Feb-Mar	174.70	123.03	1.420
Apr-May	-	-	-

(e) : Derwent at Buttercrambe 1962-1996

Season	Q_{100}	Q_5	Growth Factor Q_{100}/Q_5
Jun-Jul	-	-	-
Aug-Sep	-	-	-
Oct-Nov	135.18	70.57	1.915
Dec-Jan	136.22	88.36	1.542
Feb-Mar	**143.22**	89.53	1.600
Apr-May	86.22	63.92	1.349

(f) : Ure at Westwick 1956-1996

Season	Q_{100}	Q_5	Growth Factor Q_{100}/Q_5
Jun-Jul	-	-	-
Aug-Sep	-	-	-
Oct-Nov	360.73	228.53	1.578
Dec-Jan	451.97	287.55	1.572
Feb-Mar	**621.06**	335.29	1.852
Apr-May	-	-	-

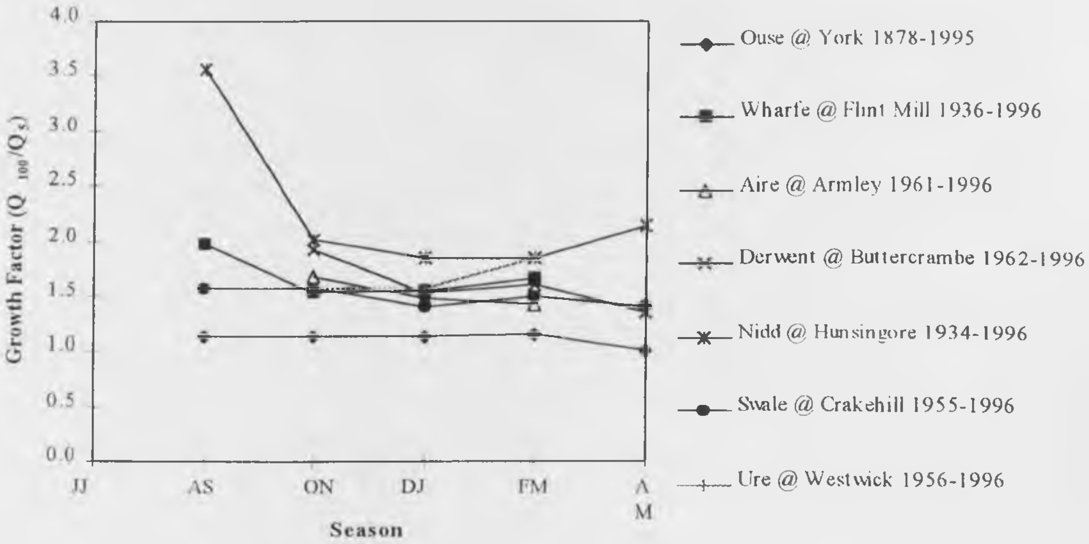
(g) : Swale at Crakehill 1955-1996

Season	Q_{100}	Q_5	Growth Factor Q_{100}/Q_5
Jun-Jul	-	-	-
Aug-Sep	209.41	133.90	1.564
Oct-Nov	248.76	158.48	1.570
Dec-Jan	244.18	174.13	1.402
Feb-Mar	**264.77**	177.08	1.495
Apr-May	201.01	142.78	1.408

These results indicate that although December-January is the most common period for flood events to occur, it is during the February-March period that the highest Q_{100} estimates are derived for six of the eight sites, again suggesting that the highest flood magnitude occur later in year The lowest Q_{100} estimates, where data are available are generally in April-May.

Growth factors displayed in figure 4.18 do not appear to vary greatly at the majority of sites, apart from on the Nidd at Hunsingore, where there are a series of large flood events in August-September.

***Figure 4.18** : Seasonal growth factors (Q_{100}/Q_S) for entire period of POT records at each site*



4.3. DOCUMENTARY FLOOD HISTORIES IN THE OUSE BASIN

4.3.1. Introduction

Due to the relatively short length of many gauging station records, evidence of flooding from archive and documentary sources have been compiled to extend the period available for analysis The main aim of this section is to investigate documentary evidence of floods for each major Ouse tributary in order to assess longer-term variations in flood frequency, magnitude and seasonality.

4.3.2. Data sources

Prior to the advent of flow gauging stations floods were often recorded on an *ad-hoc* basis, particularly if an event caused loss of life or financial damage in a populated area. Historical evidence of floods can be found in a wide range of sources in the UK, and these have been summarised by Potter (1978) for England and Wales, by McEwen (1987) for Scotland, and Hooke and Kain (1982), for the UK in general. Sources include, ecclesiastical records, personal diaries, parish records, newspapers, floodstones and compilations of large UK flood events (e.g. Acreman, 1989a; Acreman & Lowing, 1989; Brooks and Glasspoole, 1928; and Newson, 1975). By incorporating historical flood evidence into studies of flood frequency and magnitude, records of extreme flood events in particular can be extended considerably, indeed, both Archer (1987) and McEwen (1990) suggest that documentary flood records can be considered to be comprehensive back to *c.* 1750.

There is a paucity of detailed documentary flood studies in the Yorkshire area in comparison to other parts of the UK (e.g. Howe *et al.*, 1967; McEwen, 1989; McEwen, 1990; Rumsby, 1991). The main published works for the area, such as Radley and Simms (1971), Piers (1977), and Waterman (1981), all compiled records of the highest flood events in the historical archives for heavily populated areas such as York and Leeds. With the exception of the Swale (Williams, 1957) and the Wharfe area (Jones *et al.*, 1984), detailed compilations of documentary floods in the rest of the Ouse catchment has been relatively neglected, and therefore an extensive archival search was undertaken.

The main sources of historic flood information were local libraries, archive offices and regional offices of the Environment Agency. Every library and archive office at major towns throughout Yorkshire were visited and catalogues consulted, although only indexed material relating to flooding was consulted due to time constraints of the project. Ideally, the oldest local newspaper nearest to each major town in close proximity to a main Ouse tributary would be studied in detail over the entire period of publication, however the majority of newspapers were not indexed or were only partially indexed, such as the *York Courant* and *Keighley News*. These indexed newspapers, when available however, proved a valuable source of reference which could then be used to look up certain dates in more detailed local histories.

The data collected on documentary flood histories can be sub-divided into two main sources; published and unpublished compilations. Examples of published accounts relating to historic Yorkshire floods are contained in the Flood Studies Report (NERC, 1975), Radley and Simms (1971), Piers (1977), and Jones *et al.* (1984). Similarly, various local historical texts often describe the effects of large floods in specific areas, examples include Baines and Baines (1881), Hargrove (1818), Mayhall (1859) and Dawson (1882). However, a great deal of information was found from a variety of unpublished sources, which significantly, have not previously been drawn together in one study to investigate the long-term trends in flooding over the Yorkshire area. Examples of detailed unpublished sources include, Farrant (1953), Williams (1957), and the Yorkshire Water Authority (1980). A complete list of all the sources which contain information on historic flooding in the Yorkshire area is given in Appendix B.

Limitations of documentary flood records

The limitations and problems surrounding the use of documentary evidence have been described by many authors (e.g. Archer, 1987; McEwen, 1987; Rumsby, 1991). Problems include (1) the completeness of records, which tend to be more detailed in recent centuries (Suttcliffe, 1987) due to improving standards of reporting. (2) the accuracy and reliability of records is often doubtful, with historical accounts prone to exaggeration, which is compounded by the fact that many accounts are descriptive in nature and offer no systematic measurement to backup common claims such as, 'largest ever flood'. There is also the problem of non-stationarity as the result of changes in natural or anthropogenic channel controls (Archer, 1987). These can include, sluice improvements, floodplain development and general channel maintenance (NERC, 1975), all of which are difficult to quantify over an historical timescale. There is also a bias towards spatially extensive floods being recorded, rather than more localised moderate events. This spatial bias in reporting is further exaggerated since floods are generally only recorded where there are centres of population. Despite these limitations, documentary evidence of floods remains an important source of often un-tapped information with which to extend the instrumental period.

4.3.3. Variations in flood frequency and magnitude in the Ouse basin inferred from documentary sources

Documentary flood data have been compiled for each major tributary, adopting the same methodology of site selection as for the gauged record, based on proximity to LOIS study sites (i.e. piedmont and lowland areas). Only references which specifically name a particular tributary are included in each compilation. The length and detail of records for the nine major tributaries varies considerably. Table 4.12 shows that the Aire, Swale, Calder and Ouse have the highest recorded number of floods, with other rivers being much less detailed. This probably reflects location of population centres, since areas of the Aire, Calder and Ouse are densely populated, whereas the more rural catchments of the Ure, Nidd and Derwent are relatively un-populated, and floods less likely to be recorded. This is not the case for the River Swale, which has a detailed flood history from 1673 to 1953, compiled by Williams (1957), from extensive analysis of local archives and historical sources.

Table 4.12 : *Length of documentary record and number of floods recorded for each major Ouse tributary.*

River	Period of record	No of floods recorded	Comments
Aire	1068-1939	44	
Swale	1673-1953	43	
Calder	1308-1967	34	22 with level data 1799-1882
Ouse	1263-1831	24	level data since 1831
Don	1655-1940	16	
Wharfe	1673-1965	15	
Derwent	1550-1932	14	
Nidd	1763-1881	10	
Ure	1732-1927	9	

Of key importance to this study is the acquisition of the longest and most detailed records of flooding which can be used in conjunction with the gauged record. York has been identified as a key site by the York Archaeological Trust, due to recent excavations of alluvial sections in the North Street area (*cf.* Finlayson, 1993). Fortunately, floods have been well documented at York, and often have level data which can provide a direct comparison between recent and historical flood events.

4.3.3.1. Documentary flood history at York : 1263-1878

Introduction

In comparison with other sites in the Yorkshire Ouse basin, York has been the subject of several detailed studies into its documentary flood history (e.g. Farrant, 1953; Radley and Simms, 1971; Piers, 1977; Waterman, 1981) The original settlement was designed by the Roman governor of Britain, Quintus Patillius Cerealis in AD 71 (Knight, 1944) between the confluence of the Rivers Ouse and Foss, providing a defensible position, water supply and navigable river. This long history of settlement has provided detailed documentary evidence of flood events, with the earliest recorded flood in 1263.

Previous studies of documentary floods at York

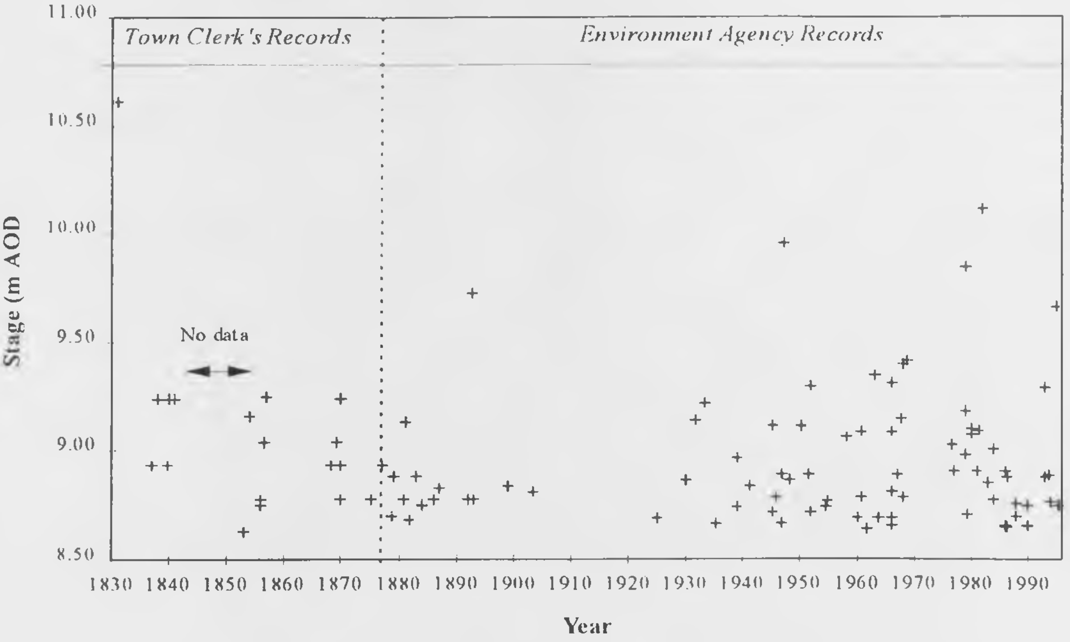
A study by Radley and Simms (1971) inferred the severity of flooding at York since Roman times based on archaeological evidence. These authors suggested that severe flooding at York was less frequent in Roman times due to lower sea level, with land as low as 4.88m AOD being occupied in certain districts of York. This period was followed by a rise in sea level and an abandonment of settlements dated to AD 350-370. This reduction in population after the Roman withdrawal was attributed to increased flooding. The authors estimated a maximum flood level of 10.67m AOD from archaeological sections at York, and an increased severity of flooding between the fifth and eleventh centuries. There followed a period characterised by reduced flood severity, which Radley and Simms (1971) suggest lasted as long as seven centuries. Although, in a study commissioned to investigate flooding at York, Farrant (1953) compiled a documentary flood history to 1263 and concluded, in contrast to Radley and Simms (1971) that there has been a gradual increase in average flood levels at York since the thirteenth century. This conclusion, based on the evidence that ecclesiastical buildings and high class residences that are now in areas liable to flooding, would not have been constructed originally if they had been subject to severe flooding, is compounded by the fact that street levels were much lower in previous centuries (Farrant, 1953; Waterman, 1981). Recent excavations by York Archaeological Trust at the North Street site suggest more complex patterns of flooding at York. A 9m sedimentary profile was excavated and logged, which was primarily composed of the remains of waterfront structures, dumped material such as shells, bricks and pottery, and sandy alluvial units. The profile was dated on the basis of pottery assemblages, and is considered to represent the period between the second and fifteenth centuries. On examination of the alluvial units Hudson-Edwards *et al.* (in press) suggest that major floods are likely to have occurred between the second to fourth centuries and the twelfth to fourteenth centuries, whereas the ninth to tenth centuries were characterised by more moderate flood events.

The main aim of Farrant's (1953) study was to investigate an apparent recent increase in 'recurrent flooding' in several districts of York It was suggested that Naburn weir, installed 9.5km downstream of York to impound water for navigation purposes, may have contributed to this increase. Naburn weir and lock were constructed in 1757, in an attempt to reduce the problem of silting, which hindered navigation to York. Prior to this time the Ouse was tidal as far as Swale Nab at the junction of the Ure and Swale (SE 430 660) (Farrant, 1953), after construction of the weir, Naburn became the new tidal limit of the Ouse. This has important implications for historical flood studies since spring tides significantly affected river levels at York prior to 1757. For example, a spring tide in 1643 caused the river to rise by 5 feet (Wilson & Spence, 1788), and combination of high spring tides and rapid snowmelt caused severe flooding at York in 1689 (Knight, 1944)

Extending the gauged record back to 1831

Flood stage data are available prior to the start of systematic recording in 1878 The records were kept by the Town Clerk's office and have been tabulated and stored at York City Library. Levels are recorded for floods that exceed 8.64m AOD at Ouse Bridge, which equates to 12 feet above summer level and would caused severe flooding in areas adjacent to the river. Levels were not recorded between 1857 and 1867, and no indication is given as to the methods of data collection, therefore the series cannot be regarded as a systematic POT record. However, inclusion of these data does extend the flood record at York considerably, and it can be assumed with some confidence that the majority of floods are recorded, since flooding above this level would cause disruption in the City centre and would be worthy of note. The record is shown in figure 4.19, and suggests that the middle nineteenth century experienced fairly high flood magnitudes, particularly in the 1830s and 1850s. Magnitudes appear to have declined from the early 1870s onwards to the record lows in the early part of the twentieth century, with the exception of a large flood in October 1892. It has been suggested in a previous section that the most recent period, from around 1978 has been atypical in terms of flood magnitudes, with particularly high events in 1978, 1982, 1991 and 1995. However, the level given by the Town Clerk records suggests that the flood of February 1831 exceed all these events. This raises the question as to the reliability and comparability of these early records, and will be discussed in a later section.

Figure 4.19 : Floods over 8.64mAOD from gauged and documentary sources



Documentary floods records at York 1263-1831

The level of historic floods prior to 1831 has often been recorded or estimated for some of the largest events at York, however different sources sometimes show large variations in magnitude. There are four main sources of historic stage data at York :

1. A table of past floods held at York City Library from 1263 to 1892 : These records were compiled from Town Clerk records and newspaper cuttings. Pre-1625 flood levels are estimated from maximum levels suggested in contemporary accounts.

2. Table of past floods between 1263 and 1982 held at York Environment Agency: This appears to have been compiled from previous historical accounts such as Farrant (1953), Radley and Simms (1971) and the Flood Studies Report (NERC, 1975). Farrant (1953) states that there are no direct references to levels prior to 1625, and therefore has estimated the flood stage for events in 1263, 1315, 1564 and 1614 on the basis of maximum level suggested in historical texts. These levels were surveyed in areas where it is assumed that changes in street levels have been at a minimum.

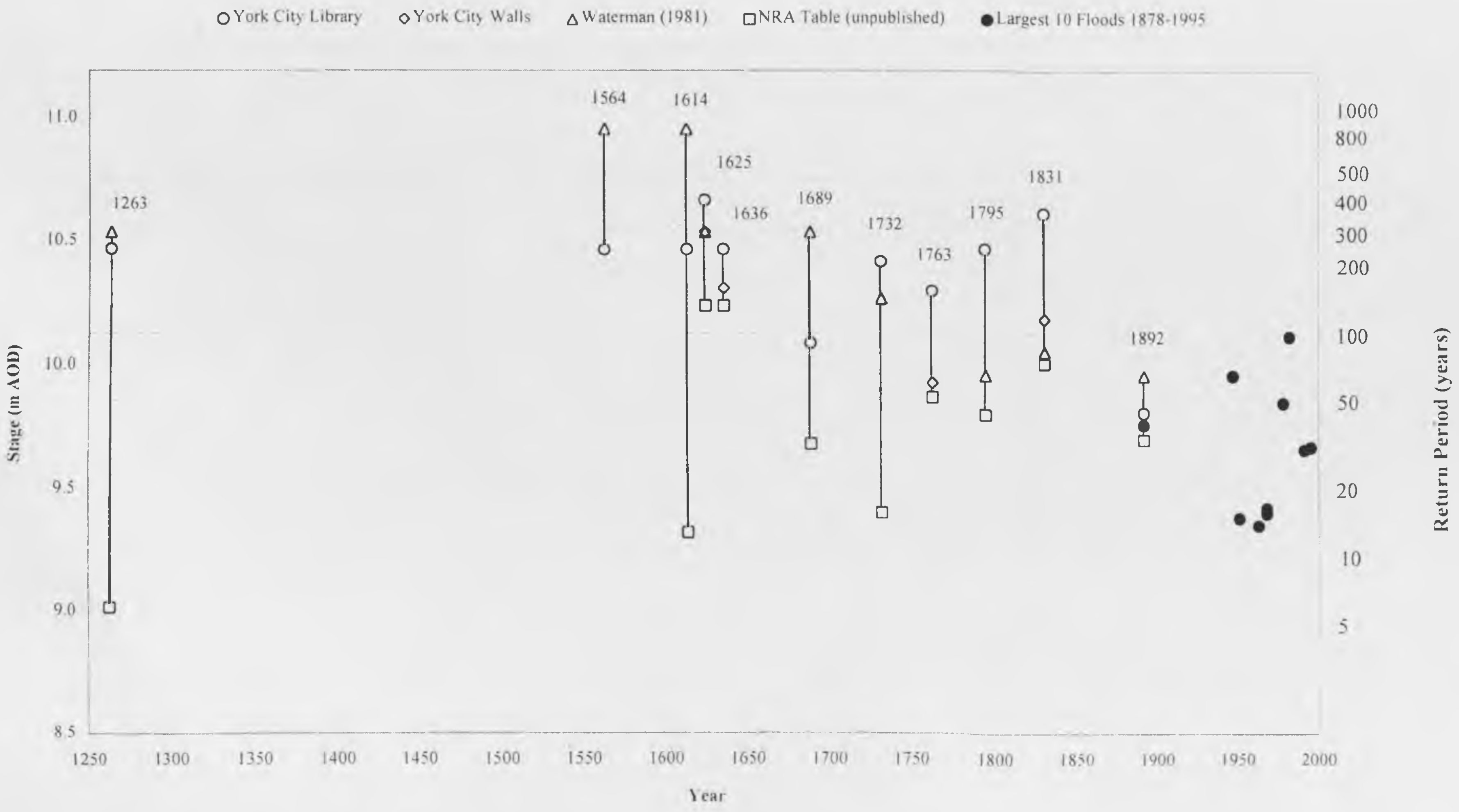
3. Flood marks on city wall plaque : The floods of 1625, 1636, 1763, 1831, 1892 and 1947 have been recorded on a plaque situated on the wall of a Franciscan friary in Tower Street (Piers, 1977). Fortunately these marks have previously been surveyed, since the plaque has recently been stolen.

4. Waterman (1981) : This author lists the flood rise above summer level for events between 1263 and 1978, there is no indication of the original source of this data, and the levels are assumed to relate to the usual historical point of reference at Ouse Bridge (Datum 4.98m AOD)

Figure 4.20 shows an updated version of work by Longfield *et al.* (1995), which illustrates the extent of variation in flood stage data between individual documentary sources. All available level data from the four sources outlined above are plotted, together with a gauged level for the 1892 flood. The horizontal dashed lines represent the level of return periods calculated using the POT model on stage data available between 1878 and 1995 at York, and provides a means of comparison between the gauged and documentary records

The range of estimates between sources can be considerable. For example, stage estimates of the 1263 flood, suggest this event could have a modern return period of <10 years or a maximum of >200 years. Similar discrepancies, although of a lesser magnitude persist throughout the entire documentary record, illustrating the considerable difficulties when considering the magnitude of historic events. Furthermore, Waterman (1981) suggests that the floods of 1564 and 1614 are the largest ever to have occurred at York, whereas Piers (1977) favours the largest event to be 1625, based on the level on the city walls. This is further complicated by Farrant's (1953) findings, since he notes that, although the city wall plaque shows the 1625 event to be some 0.23m higher than 1636, a carving on the wall shows these two events to be of equal magnitude, which the author has confirmed from early references, although he does not state which.

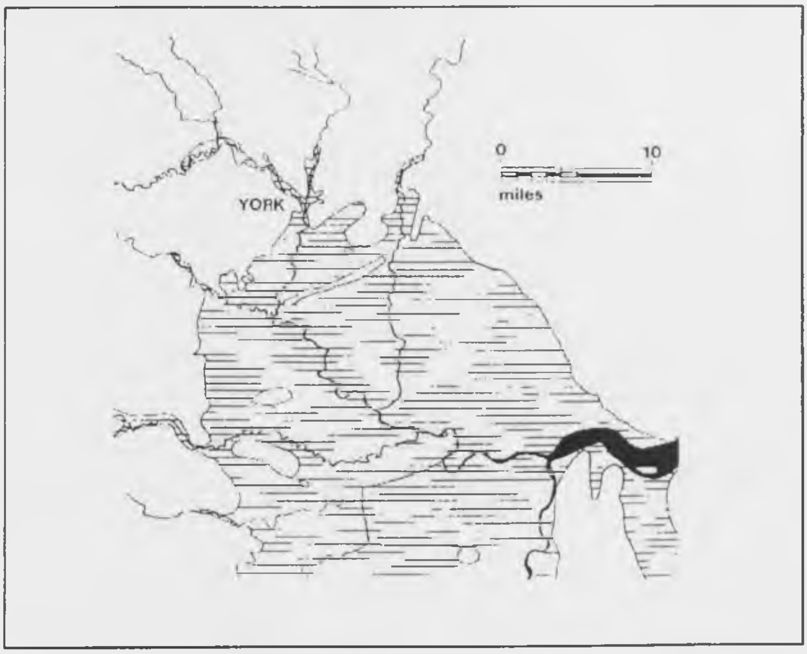
Figure 4.20 : Variation in historic flood stage data at York from different sources and comparison with the ten largest flood events from POT record 1878-1995



Return periods are calculated using POT model on stage data at York 1878-1995

Largest gauged POT floods in *1892, 1947, 1951, 1963, 1968(x2), 1978, 1982, 1991, 1995*

Figure 4.21 : Reconstructed extent of the 1625 flood at York (from Radley & Simms, 1971)



Given these problems of accuracy, inferences can still be made as to historic variations in flood magnitude and frequency. It is clear from figure 4.20 that even the minimum estimates for events in 1564, 1625 and 1636 would give a return period in excess of 100 years if viewed in the context of the recent record (since return period estimates have been calculated using the 1878-1995 record). This suggests, that these floods were indeed exceptional in two respects. Firstly, considering the lower street levels at this time, the spatial extent of flooding would be widespread, and secondly, the close grouping of these events in time. Radley and Simms (1971) have attempted to reconstruct the extent of flood water in the lower reaches of the Ouse basin for the 1625 flood, assuming a maximum level of 10.67m AOD (figure 4.21) at York. This caused widespread destruction throughout the Vale of York, and would suggest that flood levels of 10.96m AOD implied for the 1564 and 1614 events by Waterman (1981) are overestimates, since a flood 0.29m higher than 1625 would be catastrophic. Although historical texts do suggest that the floods of 1564 and 1614 were severe, it appears that the 1625 event, and possibly 1636 (Farrant, 1953) may have been the largest floods ever experienced at York.

In general, figure 4.20 suggests that exceptionally high flood magnitudes were experienced in the seventeenth century. Several extreme events occurred in the eighteenth century, although of a lower magnitude, and there was a particularly severe flood in 1831

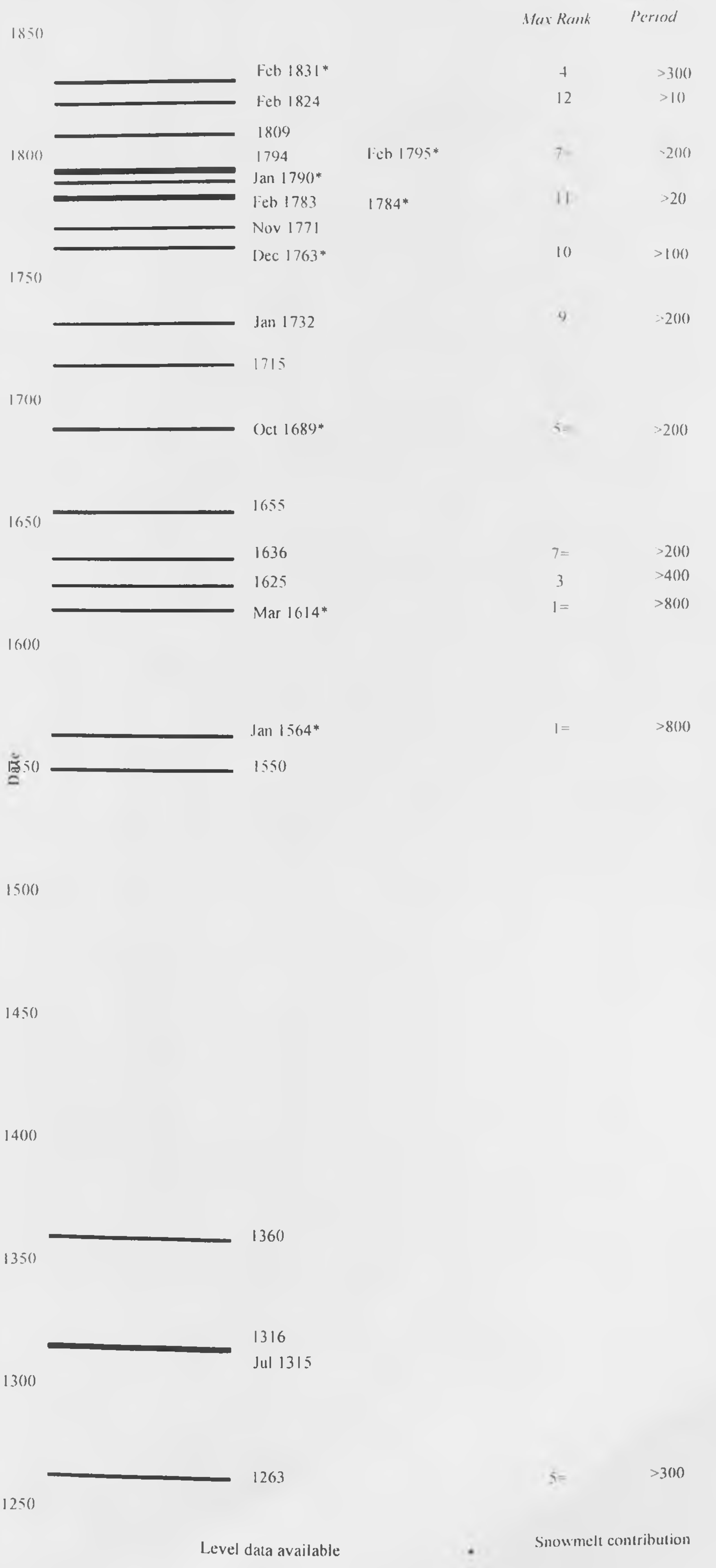
Not all flood events that have been recorded at York have stage data. a complete list of all floods referenced is given in appendix B, and shown in figure 4.22 from 1263 to 1831 The fact that these floods are chronicled at York, which is prone to frequent severe flooding, suggests that these may be considered as large magnitude events This chronology probably records all the extreme flood events at York since around 1550. In figure 4.22 those floods with level data (12 in all) have been ranked according to their maximum estimate, and an approximate return period has been established by comparison of those established from the gauged record. This flood chronology can be used to investigate flood frequency in more detail Four flood events are recorded between 1263 and 1360, however only the 1263 event level can be estimated since references state that the flood waters reached the junction of Bridge Street and North Street (10.54m AOD suggested by Waterman (1981)). No floods were recorded for almost two centuries between 1360 and 1550, although whether this represents a period of low flood frequency and magnitude is difficult to establish since records for this period are poor. A notable flood occurred in January 1564, attributed to a rapid and sudden thaw (Radley & Simms, 1971), although difficulty in establishing the magnitude of this event has already been discussed. The frequency of severe flooding increased dramatically in the min-seventeenth century and from the late eighteenth century onwards, whereas only two flood events were recorded in the early part of the eighteenth century. Those floods which have been recorded as having a significant snowmelt contribution are also highlighted in figure 4.22, and show that several of the largest events were influenced by snowmelt. There is an apparent tendency towards increased snowmelt flooding in the late eighteenth century.

4.3.3.2. Documentary flood history of the Ouse basin

Documentary evidence of floods collected for all other major Ouse tributaries is also summarised in appendix B. The earliest recorded flood in the entire Ouse basin occur on the River Aire in 1068 when William the Conqueror was held up for three weeks by the swollen River Aire (Walker, 1934). The majority of records however, date from the sixteenth and seventeenth century. The decadal frequencies of documented floods for each tributary are shown in figure 4.23, and highlight the complex and often non-synchronous timing of flood events. As discussed earlier in this chapter, this is probably a product of proximity to populated areas, where records are more likely to have been kept.

There appears to have been a period in the late thirteenth and early fourteenth centuries when several large floods were documented. Of the six events recorded between 1263 and 1360 on the Aire, Calder and Ouse, all occur independently, and are only referenced at one specific site.

Figure 4.22 : Documentary flood history at York 1263-1831



This may suggest these events represent a series of relatively localised floods, for example, on the River Aire in autumn 1322, Worseford, (1894) documents that meadow land was flooded in the Haddlesey area, and does not give any indication as to the effects elsewhere. However, some of these events were spatially extensive lowland floods, in 1263 at York for example, estimated levels suggest much of the Vale of York would have affected

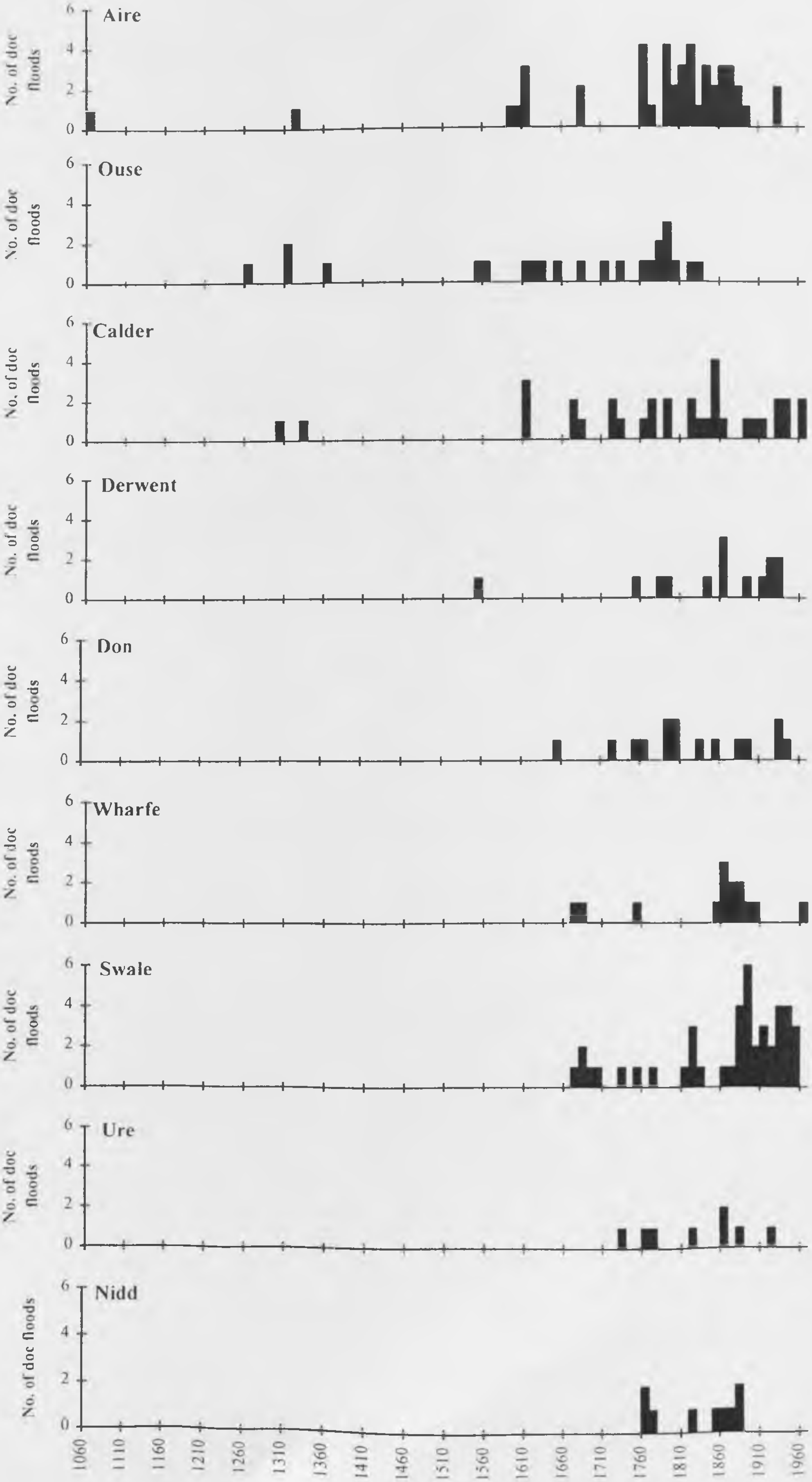
There is no recorded incidence of flooding in the Ouse basin from 1361 to 1549, although it is not until the early seventeenth century that there is real evidence of severe widespread lowland flooding. One of the largest events to occur in the Ouse basin is undoubtedly that of March 23rd 1615, when bridges at Elland at Keighley were destroyed by the Aire (Yorkshire Water Authority, 1980; Walker, Nd), and a ten day flood peak persisted at York (Radley & Simms, 1971). Interestingly, there is no evidence on any river apart from the Ouse at York, of the 1625 and 1636 flood events, which given the suggested magnitude at York would almost certainly have affected the Aire, Calder and Don valleys.

The frequency of floods recorded on these and other Ouse tributaries tended to increase towards the end of the seventeenth century. Basin-wide lowland flooding occurred in September 1673, recorded on the Calder, Wharfe and Swale, when the Calder damaged a bridge at Sowerby Bridge (Walker, Nd), and two bridges were washed away by the Swale at Brompton-on-Swale (Williams, 1957).

There followed a period from 1681 to 1763 when no floods were recorded on the River Aire, and relatively few on the Ouse at York (only in 1689 when the river was influenced by high spring tides and in 1715 and 1732). Those floods recorded on the Swale, Wharfe, Calder, Ure and Derwent over this period all tend to be localised in upland or piedmont regions. Of fifteen flood events which occurred in the Ouse basin between 1681 and 1763, only one event is recorded at more than one site. On February 2nd 1732, bridges at Masham, on the Ure (Lucas, 1887), and Brompton, on the Swale (Williams, 1957), were washed away. The remaining thirteen floods appear to have been localised to a specific tributary in an upland area, a prime example can be found in Wharfedale in 1686 and was described as follows :

> 'on the 18th February, the whole of England was visited by a tempest, accompanied with thunder, which committed great devastation. The inhabitants of Kettlewell and Starbotton, in Craven, were almost all drowned in a violent flood. These villages are situated under a great hill, whence the rain descended with such violence for an hour and a half that the hill on one side opened, and casting up water into the air to the height of an ordinary church steeple, demolished several houses, and carried away the stones entirely.' Source : Summersgill Collection, Vol 1, *Brief Accounts of Yorkshire Floods From 1564-1872*. Leeds City Library.

Figure 4.23 : Decadal frequencies of documentary floods for all tributaries



Many of these localised floods occurred between the months of May and August, and were attributed to thunderstorms or cloudbursts. On May 7th 1738 a severe thunderstorm caused the Calder headwaters to flood a chapel at Holmfirth (Morehouse, 1861), and on June 25th 1701 a cloudburst over the Swale headwaters resulted in a bridge over Grinton Beck being destroyed (Williams, 1957).

Lowland flooding appears to have increased dramatically on the River Aire in the 1760s, declined in the 1770s and 1780s, and increased again between 1790 and 1830. Evidence from the Ouse documentary and gauged records tends to support the timing of flood frequency changes on the Aire. Severe flooding appears to have become more frequent in the Ouse basin towards the end of the eighteenth century. In January 1790, a rapid thaw destroyed several bridges on the Aire, and was considered the 'greatest since 1715' on the Ouse at York. However, it was not until the nineteenth century that the majority of floods were recorded, with increases particularly evident on the Swale from the 1880s and the Wharfe in the 1860s. From this time onwards gauged data are available for the Ouse basin, and these compare well with some of the trends suggested by the documentary records. For example on the Rivers Aire and Swale, documentary records indicate that flood frequencies were high in the late nineteenth century, and low in the first three decades of the twentieth century, with flood frequencies increasing on the Swale from around 1930 onwards. This compares well to the timing of variations in flood frequency established from the gauged records.

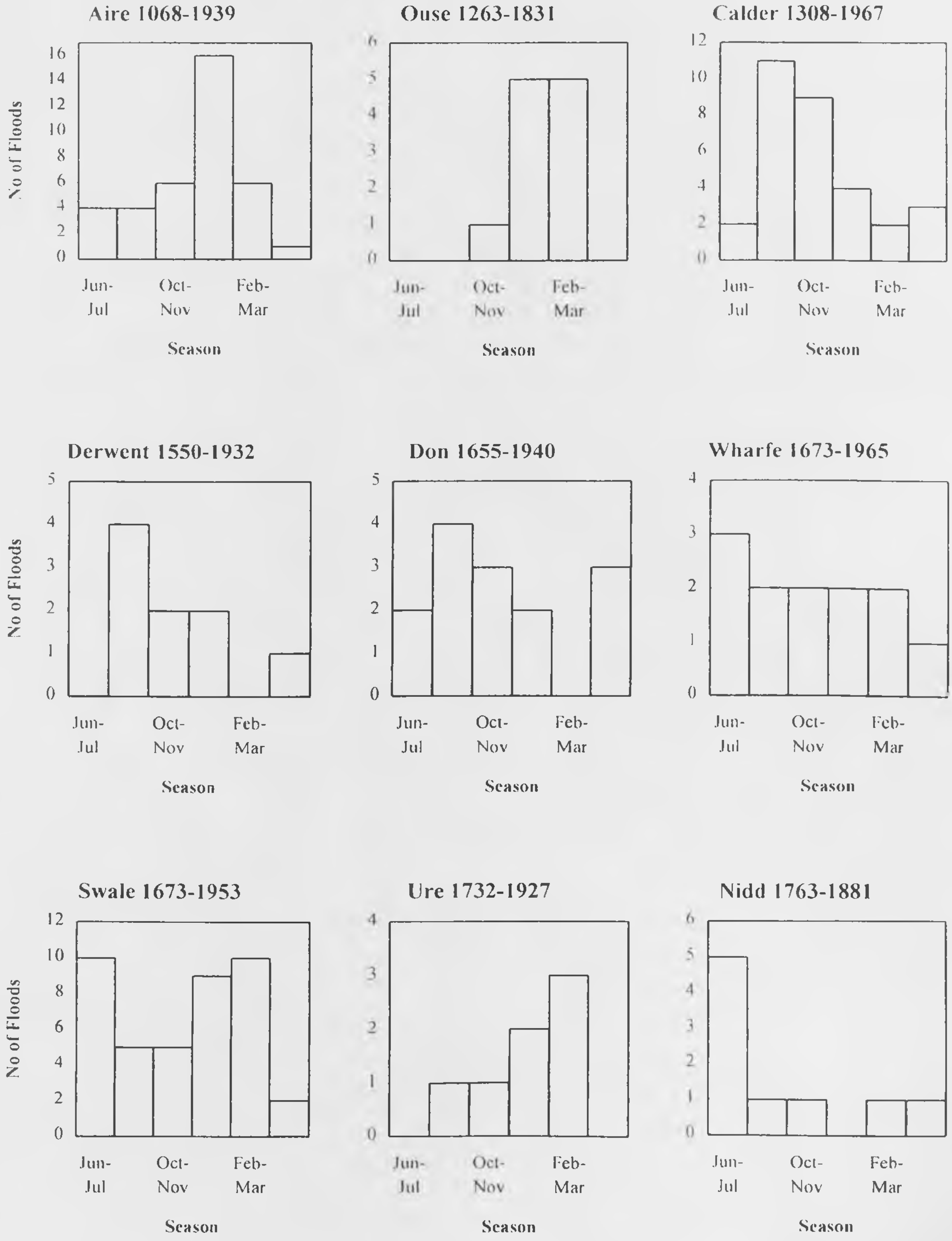
4.3.3.3. Seasonality of documentary floods

The main patterns in seasonality identified from the gauged record suggest that the highest frequency of floods occur in the December-January period, and the highest magnitude events in the February-March period. To compare the seasonality of documentary floods, the frequency of events in 2-monthly periods has been plotted in figure 4.24. Unfortunately, some documentary evidence gives no indication as to the month of flood, therefore these series do not represent the entire flood record. Unlike the gauged records, there is considerable variability between tributaries. The dominant flood season for the Aire is December-January, whilst December-January and February-March are equally important on the Ouse at York, which may reflect the increased influence of snowmelt in the large, predominantly rural Ouse catchment. This winter flood dominance is not reflected within the other documentary records, on the Calder, Don, Wharfe, Derwent and Nidd the highest frequency of floods occur in the four months between June and September. These variations are likely to be a result of the location in each catchment where floods were recorded. Floods recorded in summer months tend to be localised upland events, whereas winter floods tend be spatially extensive lowland events. The

River Swale, which has one of the most detailed documentary records in the Ouse basin, provides a good example, where both types of events have been recorded. Localised upland floods caused by cloudbursts or thunderstorms are recorded in April 1821, July 1888 and June 1899, extensive lowland floods occurred in November 1866, as a result of heavy rainfall, and in December 1814 due to snowmelt (Williams, 1957).

Variations in the long-term seasonality of the Ouse basin are difficult to assess for two reasons, firstly, the location of recording varies through time, which can alter the type of flood event recorded (e.g., upland summer thunderstorm or lowland flood caused by intense rainfall). Secondly, many events, particularly prior to the eighteenth century do not have the flood month recorded.

Figure 4.24 : Seasonality of documentary floods for individual tributaries



Aire 1068-1939

Ouse 1263-1831

Calder 1308-1967

Derwent 1550-1932

Don 1655-1940

Wharfe 1673-1965

Swale 1673-1953

Ure 1732-1927

Nidd 1763-1881

4.4. SUMMARY OF FLOOD VARIABILITY IN THE YORKSHIRE OUSE BASIN SINCE THE ELEVENTH CENTURY

The previous sections have illustrated that there have been distinct variations in flood frequency, magnitude and seasonality over the last nine centuries or so. This section aims to summarise the patterns, and to identify anomalies from these general trends

4.4.1. Variations in flood frequency and magnitude

The earliest documentary evidence of flooding in the Ouse basin occurred in 1068 when the progress of William the Conqueror was held up due the River Aire being in flood. Records for this early period are poor and it is not until the mid-thirteenth century that there is evidence of widespread flooding in the Ouse basin, with a series of large events recorded between 1263 and 1360. From this time no floods were documented in the basin until 1550, and frequencies remained relatively low until the mid-seventeenth century when there were a series of catastrophic flood events, which are possibly the largest events ever experienced in the Ouse basin in the historic period. Although magnitudes were high, flood frequency remained low, particularly over the period 1681-1763 when only localised summer floods caused by thunderstorms and cloudbursts were recorded rather than basin wide events The frequency of large lowland floods increased markedly towards the end of the eighteenth century and remained high in the early part of the nineteenth century.

Gauged flood records are available in the Ouse basin from just after the mid-nineteenth century and also show distinct variations in flood frequency and magnitude The later half of the nineteenth century was characterised by high flood magnitudes, evident in both the northern and southern parts of the Ouse basin. Flood frequencies displayed a higher degree of variability, with high frequencies common throughout the 1870s and early 1880s, followed by a decline in frequencies from the 1880s onwards. Over the period *c.*1900-1920 there is evidence of a rapid decline in flood magnitude from elevated nineteenth century levels, to the lowest magnitudes experience throughout the whole record. Flood frequencies continued to decline and remain extremely low throughout this period. During the 1920s, both magnitudes and frequencies increased slightly on the Ouse at York and Aire and Calder at Castleford. However, the records on the Don at Doncaster and the Calder at Broadreach significantly deviate from this pattern. The 1920s represent the beginning of a gradual decline in flood magnitudes on the Calder at Broadreach, which continue until 1968. Whereas, a number of large floods occur on the Don over this period. Relatively low flood frequencies and magnitude dominate between *c.*1930-1944, the exception again being the River Don, where there were a number of large events during this time. There followed a period of high flood magnitude and a sustained increase in flood frequency around 1944 until around 1950. In the 1950s flood frequencies showed a high degree of inter-annual variability, whereas flood magnitudes declined considerably Frequencies stabilised, and were generally high throughout the 1960s, as were flood magnitudes which peaked around 1965, however, from 1969 onwards, frequency and magnitude series both varied markedly. The 5-year period from 1972-1976 showed the lowest average flood magnitudes on record at five of the eight sites, and lowest average frequency at six From around 1977 magnitudes and frequencies increased dramatically from the record lows of the early and mid 1970s. Indeed, the 1977-1981 5-year period showed the highest average flood frequencies at seven of the eight sites. Frequencies reached a high in the early 1980s, and have since declined in the 1980s and 1990s. However, this decline is not as marked in the Ouse at York. Flood magnitudes displayed a slightly different trend, showing a similar peak in the late 1970s to early 1980s, followed by a decline in the mid 1980s, but with magnitudes again increasing in the 1990s.

Anomalies from the trends described above may be an indication of the influence of land-use change, since climatic induced variations would be expected to influence all tributaries at the same time. In general, it appears that flood records of the rural northern tributaries of the Ouse (i.e Derwent, Swale, Ure, Nidd, Wharfe and Ouse) show a high degree of correlation, although the scale of changes does vary. The more industrialised and urbanised catchments in the southern part of the basin (i.e. Aire, Calder and Don), tend to show unique temporal variations. For example, the Calder at Broadreach displays a continuous decline in flood magnitude from the 1920s, and the Don at Doncaster has a series of extreme flood peaks from the 1920s to the 1940s, not evident elsewhere in the Ouse. Anomalies do, however, occur on some of the northern rivers, on the Ouse at York for example flood frequencies have remained well above average since around 1982, which coincides with the construction of the Foss Barrier flood defence scheme, some 400m downstream of the gauging site.

4.4.2. Variations in flood seasonality

Seasonality of documentary floods shows considerable variation which is probably a reflection of where events were recorded. In upland and piedmont areas localised summer floods are more reported, in lowland areas more severe spatially extensive winter flooding is recorded. Lowland sites such as the Aire and Ouse have the highest frequency of events between December and March, whereas the majority of the other tributaries show the highest flood frequencies between June and September. Only in detailed records which record both upland

and lowland events, such as on the River Swale, are high flood frequencies recorded in both these periods

These patterns differ markedly from those shown in the gauged record The highest frequency of flooding occurs in the December and January months, although higher magnitude events tend to occur later in the year, typically in February and March Summer flooding is relatively rare within AM and POT records. Temporal variations are also evident, with increases in spring flooding occurring the late 1940s, mid-late 1960s and late 1970s to early-1980s, again associated with increases in magnitude. The occurrence of Autumn floods has declined since the 1960s, coinciding with an increase in spring events

CHAPTER 5

CLIMATIC VARIABILITY IN THE OUSE BASIN SINCE THE ELEVENTH CENTURY

5.1. INTRODUCTION

The spatial and temporal variability of Ouse basin flood records has been established in Chapter 4. The next stage is to address the question as to what has caused and controlled these observed changes. This chapter uses instrumental (last 135 years) and proxy (last 900 years) climate data for the Ouse basin and UK to investigate the long-term relationships between climate and flood variability. Three main climatic parameters are investigated, rainfall, snowfall and atmospheric circulations.

It is often assumed that variability in flood records will mirror changes in rainfall patterns, and therefore analysis of rainfall can be limited in explaining patterns within flood records (Grew, 1996). However, in this case it was felt that detailed analysis of long-term rainfall records would be beneficial since regional trends of climatic variability could be established. Snowmelt also plays an important part in flood generation, particularly in north-eastern England (Archer, 1981). Unfortunately, records of snowfall and snow depth are poor when compared to rainfall records. However records of heavy snowfalls and particularly bad winters are available, albeit on a country-wide scale, from the late nineteenth century and have been incorporated into this study.

Although analysis of instrumental and proxy records of precipitation can give an indication of general climatic change in the Ouse basin over the last 900 years, it is the circulation of the atmosphere that ultimately dictates the character of UK weather, and it is analysis of these circulation types that can most effectively define and explain climatic variability (Kelly *et al.*, 1997). As discussed in Chapter 2, the majority of previous studies that have investigated the relationships between atmospheric circulation and flooding, have inferred variations in circulation types from annual (Higgs, 1987a; 1987b, Rumsby and Macklin, 1994) or monthly

(Knox *et al.*, 1975) totals. Similar to precipitation records, analyses of this type will only give an indication of general trends in climate that affect flooding, and not the specific circulation types and weather conditions that generated a particular flood event. Grew (1996) has addressed this problem by classifying each individual flood event from a large number of Scottish POT records according to the circulation type on the day of flood and the previous day. However the number of days prior to a particular flood event that generate the flood may vary depending upon catchment characteristics, particularly the size and gradient of the basin. In this study a method has been developed using daily rainfall records to assess the number of days prior to each flood event at each site which have caused the flood. The circulation type on these particular days can then be determined and a dominant circulation type assigned to each event. The principal advantage of this approach is that the flood is classified according to the circulation type that provides the precipitation input, rather than assuming that the circulation type on the day of the flood is the primary generator.

There are two main aims of this chapter. First, to establish long-term variability in precipitation records and assess whether this is reflected in the flood record. Secondly, to investigate the role of atmospheric circulation types in generating flood events in the Ouse basin, and how this relates to more general annual and seasonal variability of circulation types through time. The chapter is split into two sections, the first evaluates the instrumental climate records and the second longer-term proxy and documentary climate records

5.2. DAILY RAINFALL RECORDS IN THE OUSE BASIN 1873-1996

5.2.1. Introduction

Previous studies of rainfall in Yorkshire and Pennine areas have focused on localised extreme events (e.g. Chaplain, 1982; Meaden, 1984; Acreman, 1989b), the construction and investigation of composite rainfall records (e.g. Milner, 1968; Jones, 1981), investigation of long records at an individual site (e.g. Smithson, 1976; Gregory, 1993), and the detailed study of the topographical controls of rainfall in a small area (e.g. Burt, 1984). None of these studies have the spatial or temporal resolution required to assess long-term variability of rainfall over the entire Ouse basin. Ideally a dense network of raingauges in excess of 100-years length would provide this resolution, however, as with any historical study this is controlled by the availability of data. This section investigates variations in the longest daily rainfall records available in the area by analysing annual and seasonal rainfall totals and the occurrence of extreme heavy daily rainfalls using POT records.

5.2.2. Data sources

The first systematic measurements of precipitation in the UK began in 1677, and there are currently over 8000 operational rain gauges (Jones *et al.*, 1997). However, the majority of gauging did not start until the 1860s when G.J.Symons established the British Rainfall Organisation. In the Ouse area the longest continuous record of daily rainfall is at Blackmoorfoot (SE 096 130) and dates to 1873. Records of daily rainfall used in this study have been selected on the basis of length and continuity. Most of the long continuous records are in lowland areas, however, occasionally some records are available in headwater or piedmont parts of the catchment.

Data were initially selected from a catalogue supplied from the Dales Area Office of the Environment Agency at York. This listed data on their RAINARK data logging and processing system which were available for analysis. A problem identified at this stage was that many of the records that were listed were not complete daily series, and often contained a large amount of monthly data. Since rainfall records were required to investigate flood generation, it was decided that only complete daily rainfall records would be used in this study, and those containing monthly data were rejected. Further daily rainfall records were obtained from the Meteorological Office, some supplied on disk by Met Office commercial services, and others compiled directly from original paper records held at the Meteorological Office Archive. A complete list of sites used in this study, and where they were obtained, is given in table 5.1 and their location shown in figure 5.1. Only five of these sites however, were used in the analysis of long-term trends.

5.2.3. Preparation of rainfall data

Two separate series of rainfall data were constructed from raw data First, total annual rainfall, and annual seasonal rainfall totals were compiled using daily records. Seasons are classified in three monthly periods; winter is defined as December-January, spring as February-April, summer as May-July, and autumn as August-November. Secondly, a POT series for each site was constructed to investigate the incidence of heavy daily rainfall. The POT threshold was set to give an average of ten peaks per year over the standard period 1941 -1995. This threshold contains a higher number of peaks per year than the flood records since not every day of rainfall over the threshold will contribute to a flood event, and therefore a larger number of rainfall days need to be considered. In general the techniques of data analysis are similar to those described for the flood record outlined in section 4.2.3.

***Figure 5.1:** Location of rain gauges*

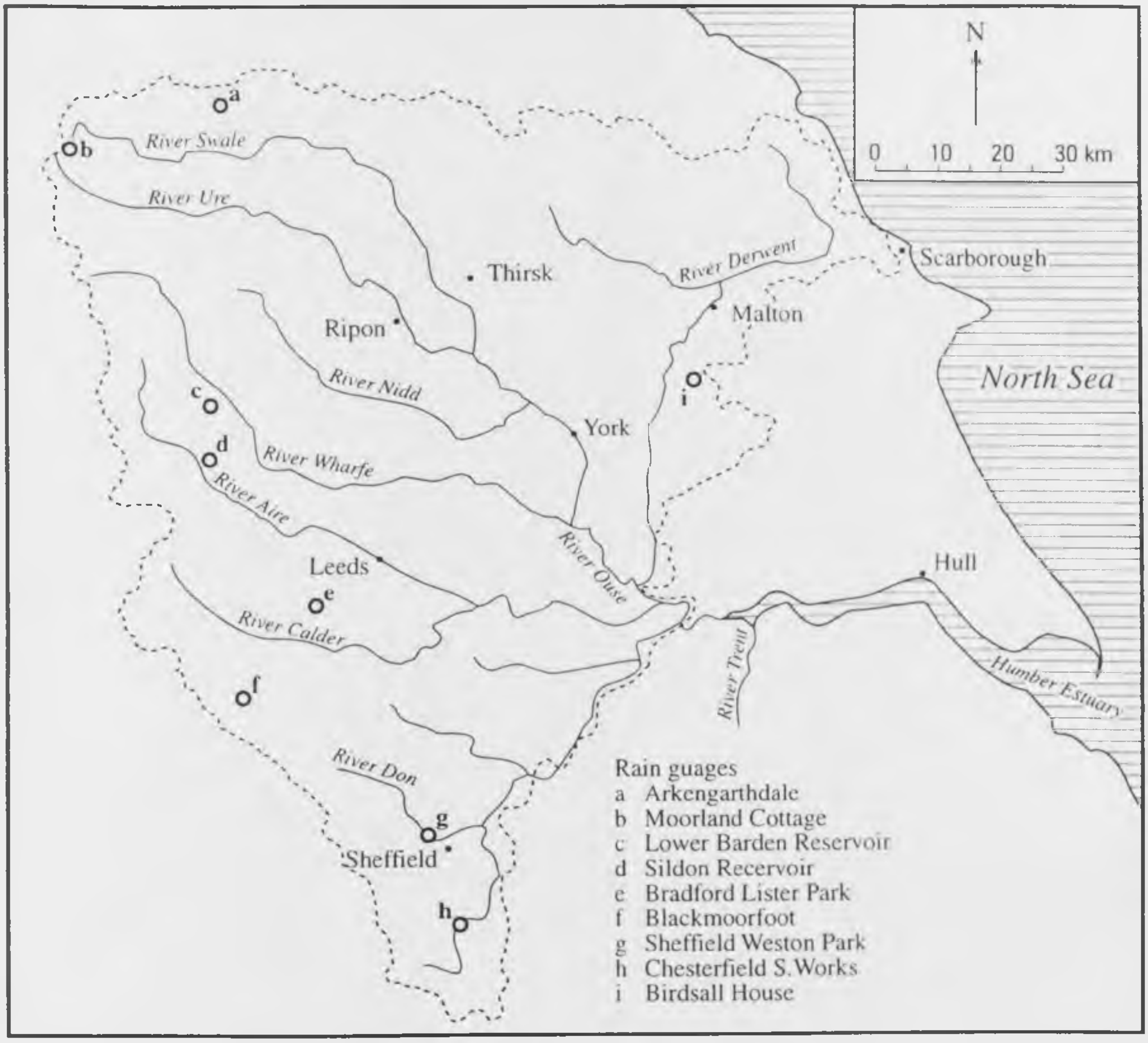


Table 5.1 : Summary of rain gauges used in long-term analysis

Station Name	**Met Office Ref No.**	**Grid Ref**	**Length of Record**	**Altitude mAOD**	**No of years data missing**	**POT threshold (mm)**	**Source**
Blackmoorfoot Reservoir N	78622	SE 099 131	1982-1996	244	0	20.1	EA
Blackmoorfoot Reservoir	78623	SE 096 130	1873-1982	250	0	20.1	MOA
Chesterfield S.Works N	83819	SK 391 742	1980-1996	-	0	13.7	EA
Chesterfield S.Works	83821	SK 392 746	1906-1979	-	0	13.7	EA
Moorland Cottage	47060	SD 807 923	1936-1995	343	0.3	31.5	EA
Sheffield Weston Park	82583	SK 339 873	1883-1996	131	0	15.0	MOCS
Bradford Lister Park	75632	SE 149 352	1911-1996	-	0	15.5	EA

EA : Environment Agency
MOA : Meteorological Office Archive
MOCS : Meteorological Office Commercial Services

5.2.4. Variations in annual and seasonal rainfall series

Annual and seasonal rainfall totals for five long-term rain gauges in the Yorkshire area are shown in figures 5.2-5.6. These records indicate that the late nineteenth century was characterised by relatively low annual and seasonal totals with the exception of the summer season which experienced higher totals in the 1870s and 1890s. This contrasts with the flood record which suggests that both flood frequencies and magnitudes were high at this time. There is evidence of a rise in annual rainfall at Blackmoorfoot and Sheffield Weston Park from the turn of the century which appears to relate to an increase in winter and spring rainfall particularly at Blackmoorfoot. Large inter-annual variation in rainfall is evident between 1900 and 1950 however there appears to be little overall trend during this period apart from at Blackmoorfoot where there is a decline in winter and spring rainfall in the mid-to-late 1930s followed by a slight increase in the 1950s. From the 1950s onwards there appears to have been a number of significant variations in rainfall totals particularly in spring (which is also reflected in the overall annual totals). Spring totals were relatively low in the mid-1950s, but rose to a particularly marked peak in the mid-1960s, which is associated with high flood magnitudes and an increased incidence in spring floods. Throughout the 1950s and 1960s winter and summer totals remained close to the long-term mean, although there is some evidence of slightly increase autumn totals in the mid-1960s. There followed a decline in annual rainfall in the late-1960s to mid-1970s particularly evident in spring, summer and autumn. The late-1970s to mid-1980s again saw a marked increase in spring rainfall, associated with the most marked period of spring flooding in the entire historic record. Although, whilst the 5-year running mean remains high over this period, there is actually a high degree of inter-annual variation between spring totals. Since the mid-1980s both annual and seasonal rainfall totals have declined except in winter which appear to be increasing throughout the 1990s

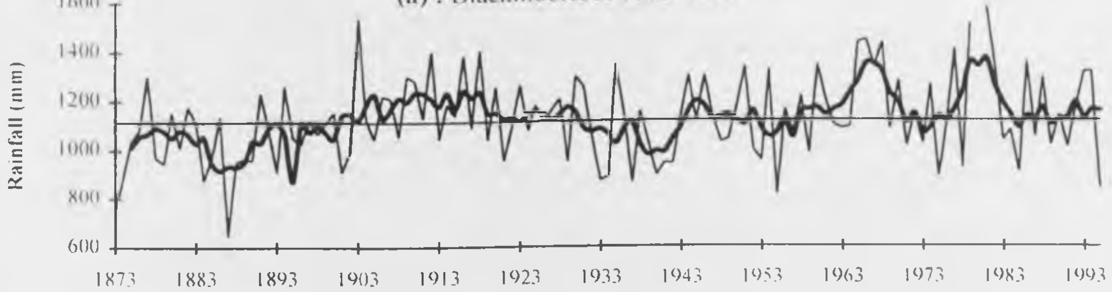
5.2.5.Variations in POT rainfall series

5.2.5.1. Annual POT rainfall frequency

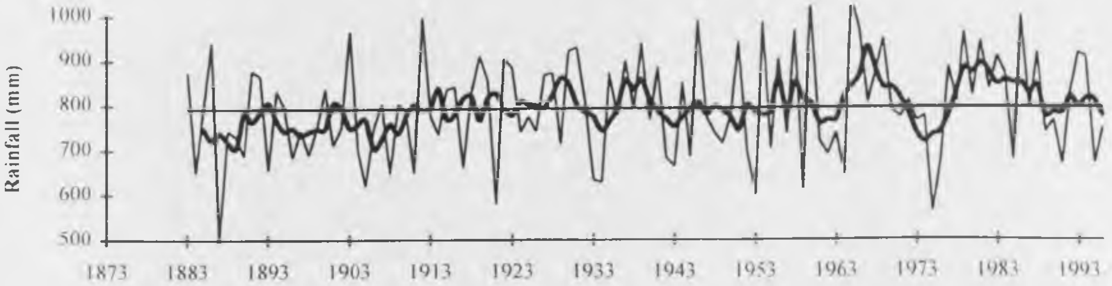
Annual frequencies of POT rainfall events are shown in figure 5.7. The late nineteenth century was characterised by low rainfall frequency particularly in the 1870s and 1880s, whereas higher frequencies were more common in the 1890s and 1900s. In the first three decades of the twentieth century frequencies were relatively low at Blackmoorfoot, Sheffield Weston Park and Chesterfield, although not at Bradford Lister Park where the 5-year running mean indicates that high frequencies were common between 1911 and 1930. At the two highest altitude rain gauges, Moorland Cottage and Blackmoorfoot there is evidence of a peak in frequencies in the mid-1940s, this trend is not apparent in any of the lowland records. This peak was followed by

Figure 5.2 : Annual rainfall at five long-term raingauges

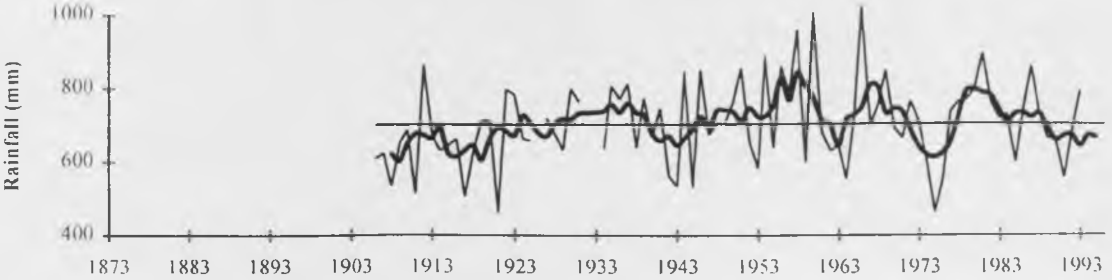
(a) : Blackmoorfoot 1873-1995



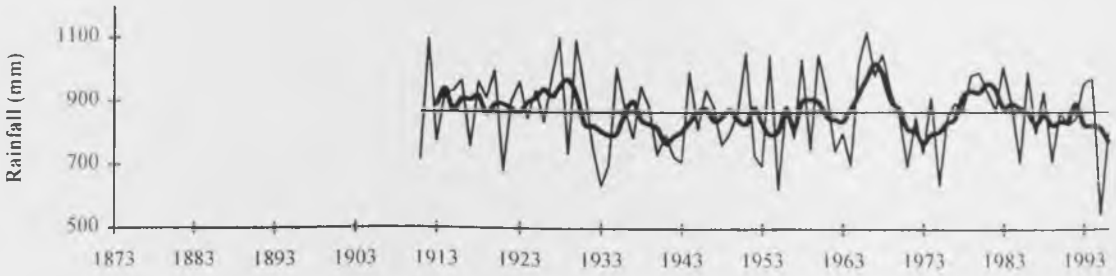
(b) : Sheffield Weston Park 1883-1996



(c) : Chesterfield 1906-1996



(d) : Bradford Lister Park 1911-1996



(e) : Moorland Cottage 1936-1995

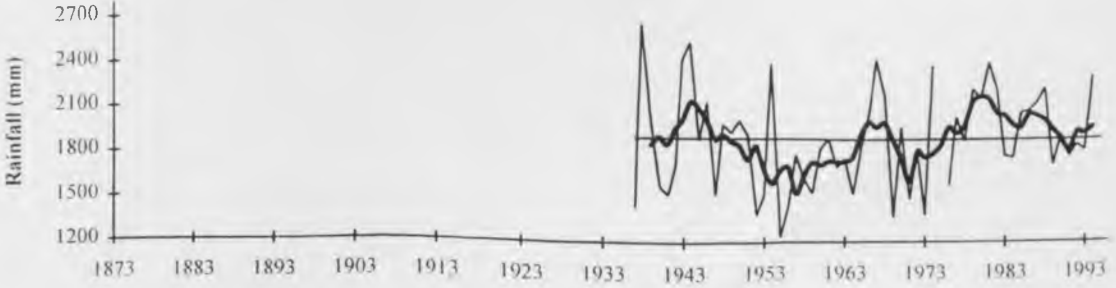
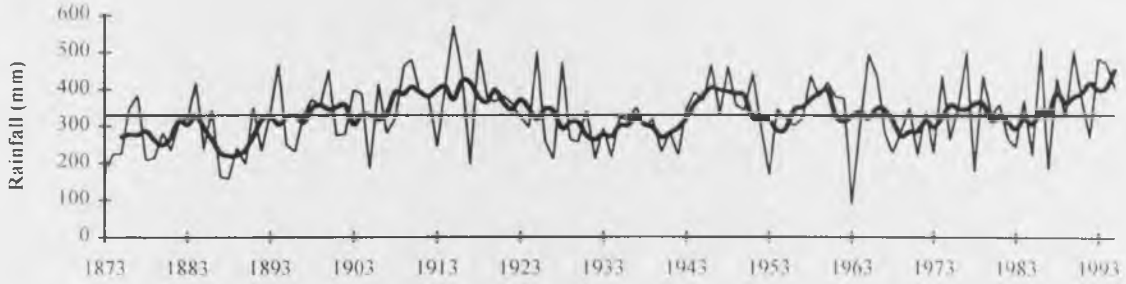
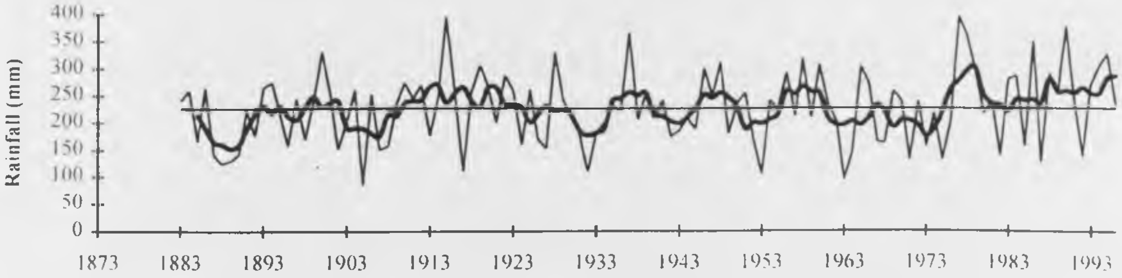


Figure 5.3 : Annual winter rainfall at five long-term raingauges

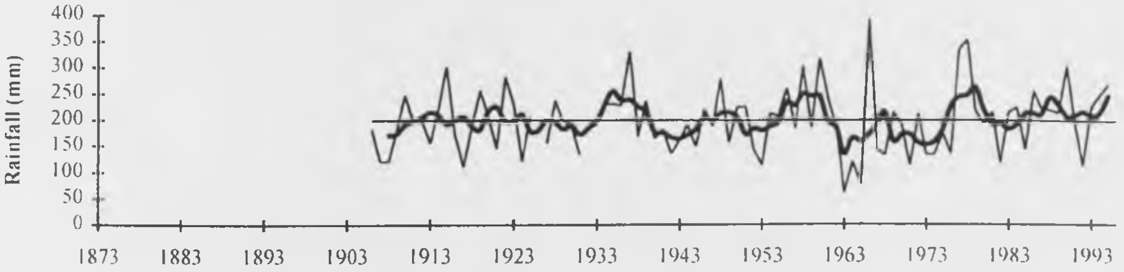
(a) : Blackmoorfoot 1873-1995



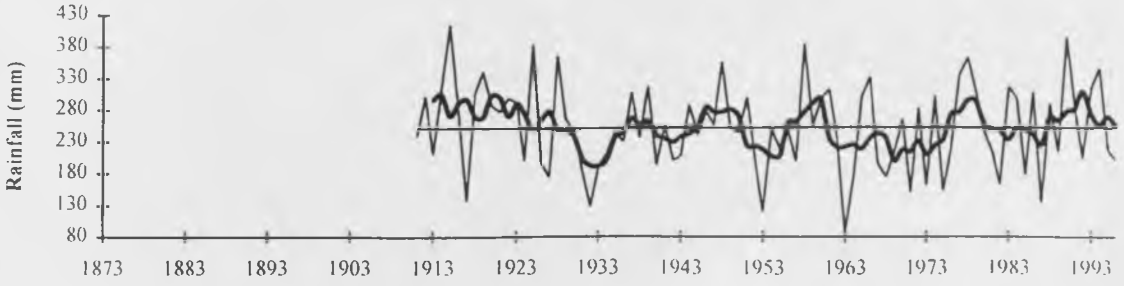
(b) : Sheffield Weston Park 1883-1996



(c) : Chesterfield 1906-1996



(d) : Bradford Lister Park 1911-1996



(e) : Moorland Cottage 1936-1995

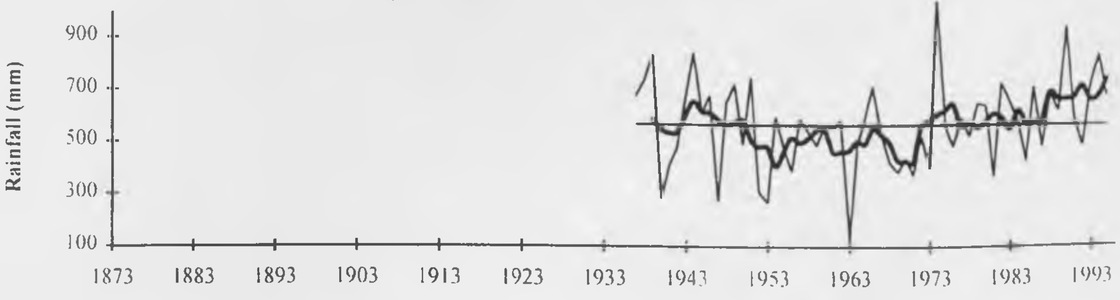
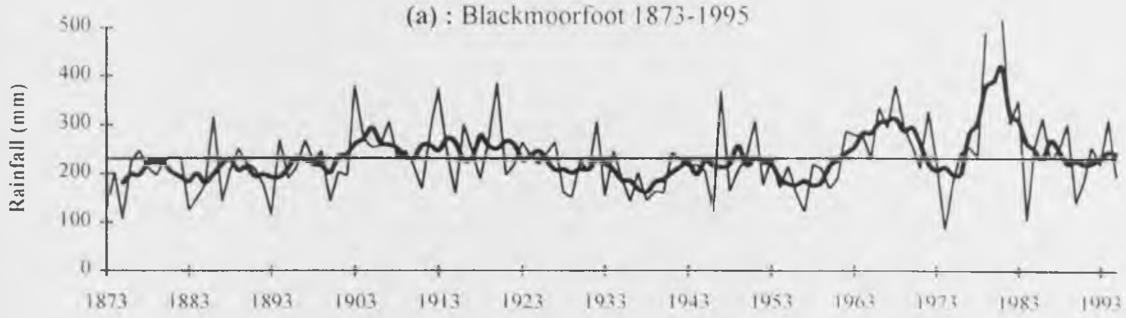
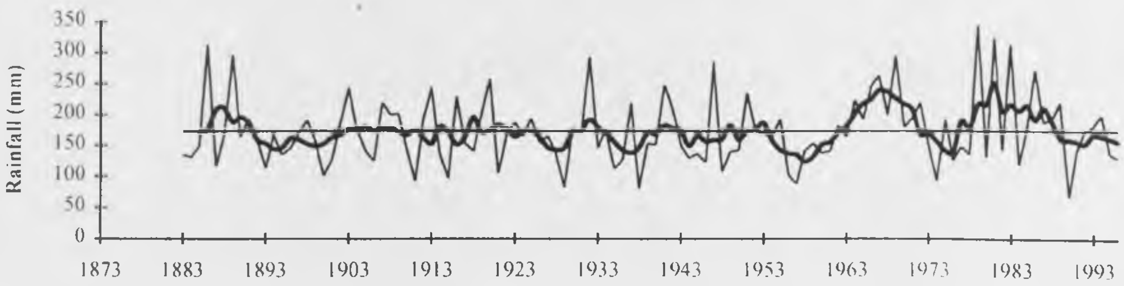


***Figure 5.4** : Annual spring rainfall at five long-term raingauges*

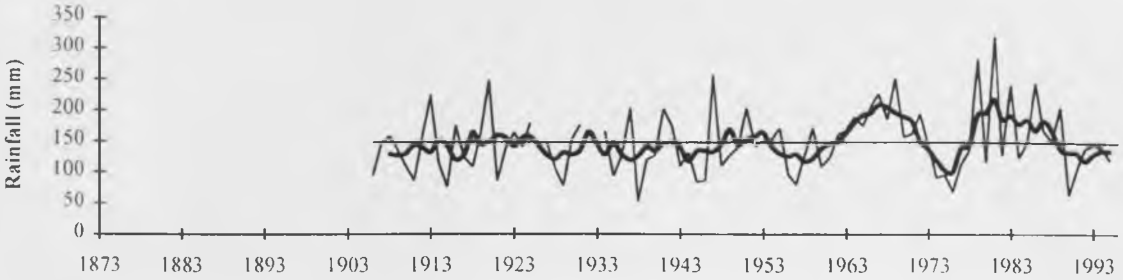
(a) : Blackmoorfoot 1873-1995



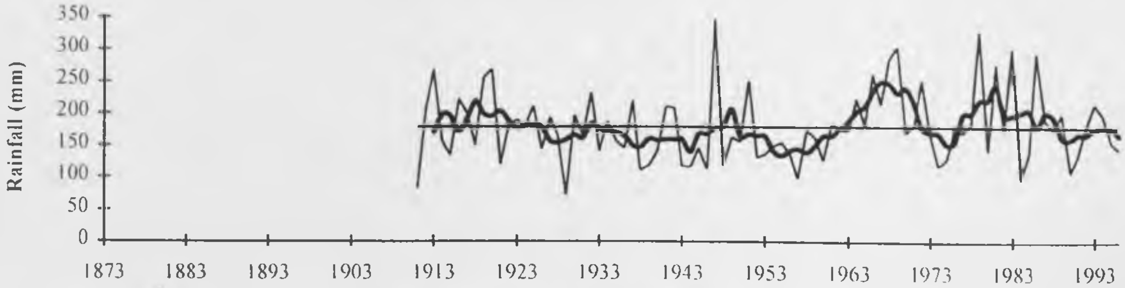
(b) : Sheffield Weston Park 1883-1996



(c) : Chesterfield 1916-1995



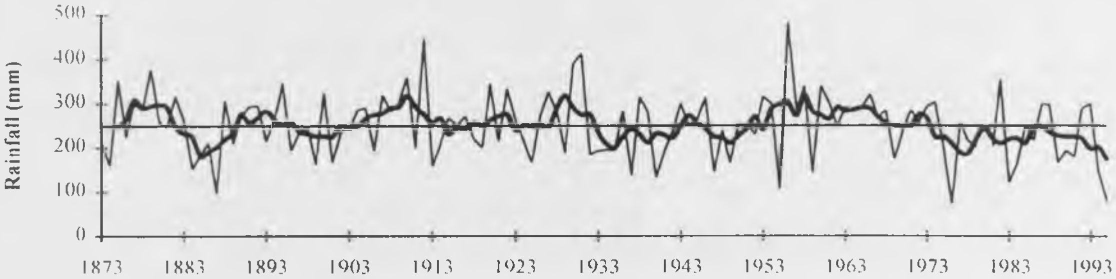
(d) : Bradford Lister Park 1911-1996



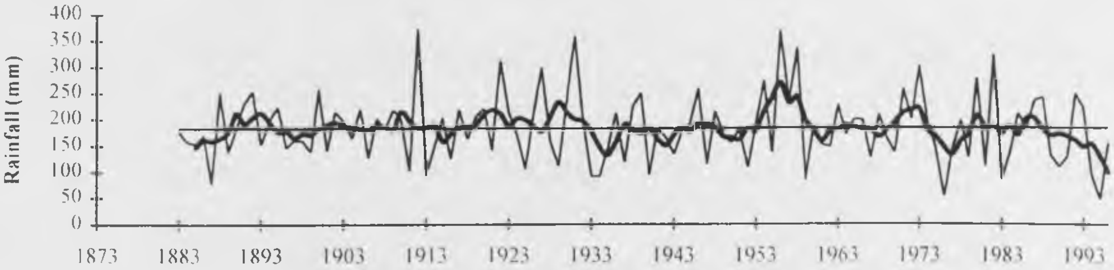
(e) : Moorland Cottage 1936-1995

Figure 5.5 : *Annual summer rainfall at five long-term raingauges*

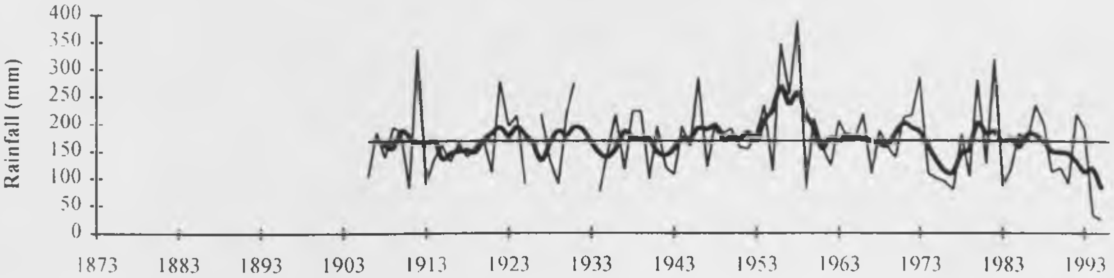
(a) : Blackmoorfoot 1873-1995



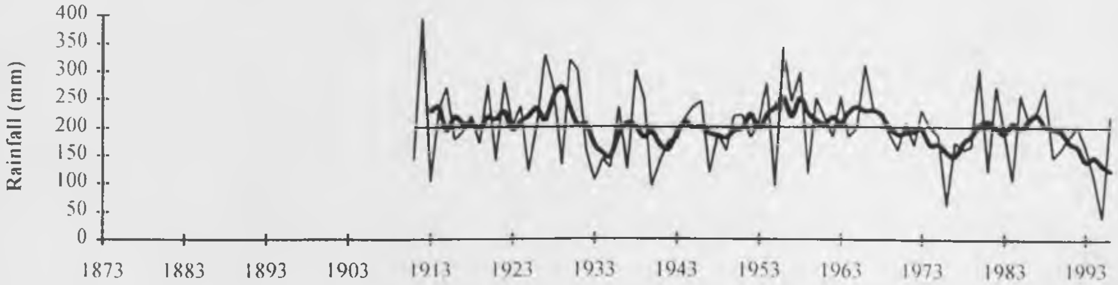
(b) : Sheffield Weston Park 1883-1996



(c) : Chesterfield 1906-1995



(d) : Bradford Lister Park 1911-1996



(e) : Moorland Cottage 1936-1995

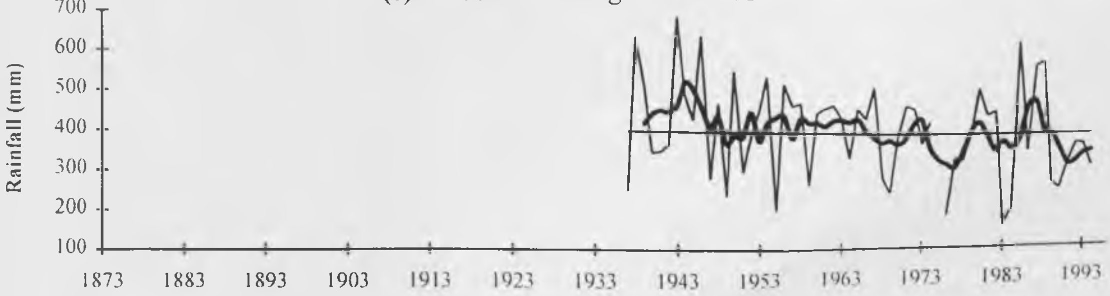
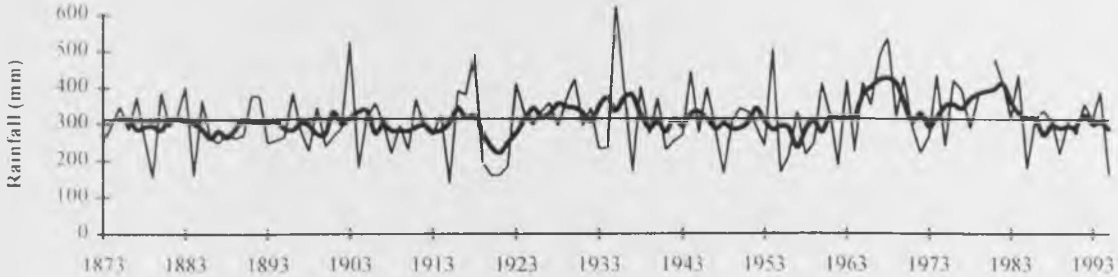
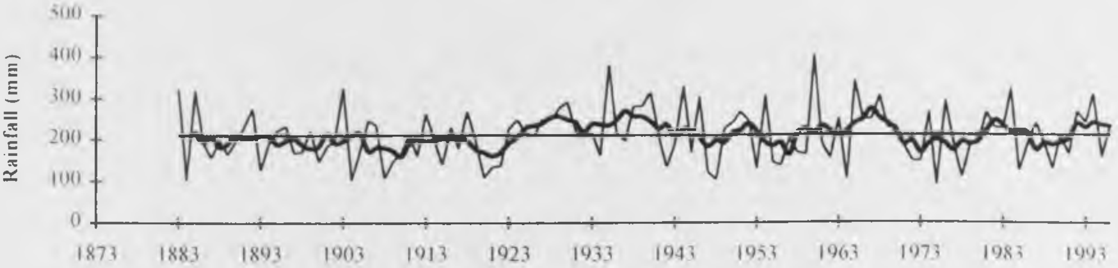


Figure 5.6 : Annual autumn rainfall at five long-term raingauges

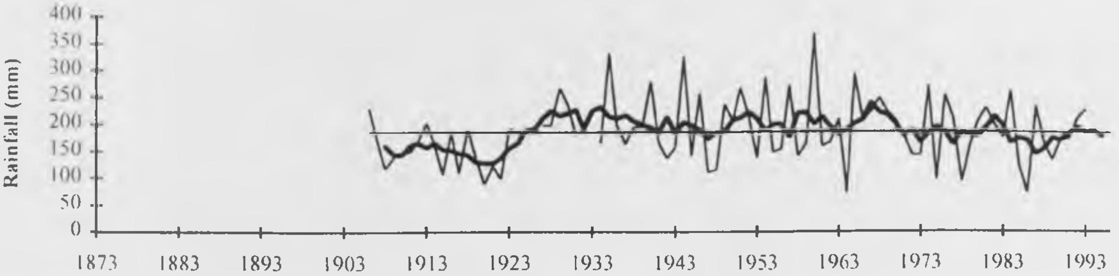
(a) : Blackmoorfoot 1873-1995



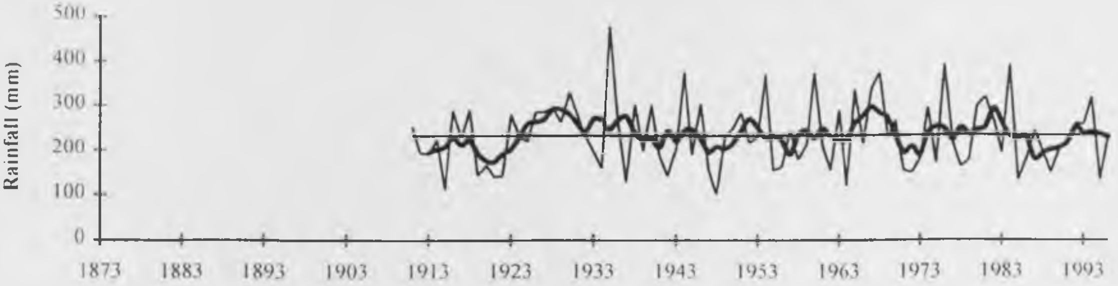
(b) : Sheffield Weston Park 1883-1996



(c) : Chesterfield 1906-1995



(d) : Bradford Lister Park 1911-1996



(e) : Moorland Cottage 1936-1995

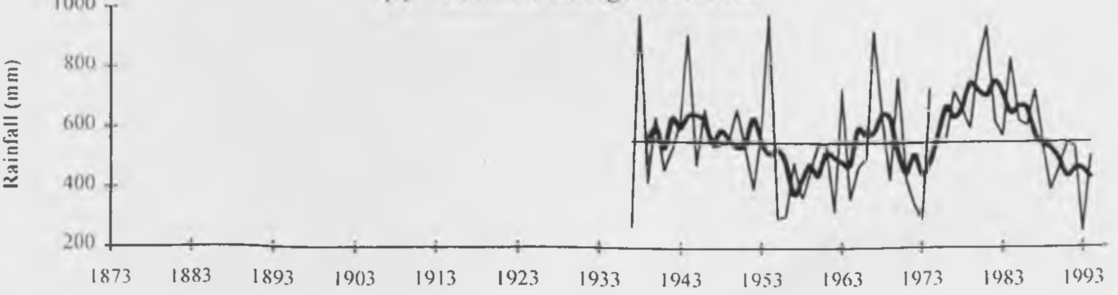
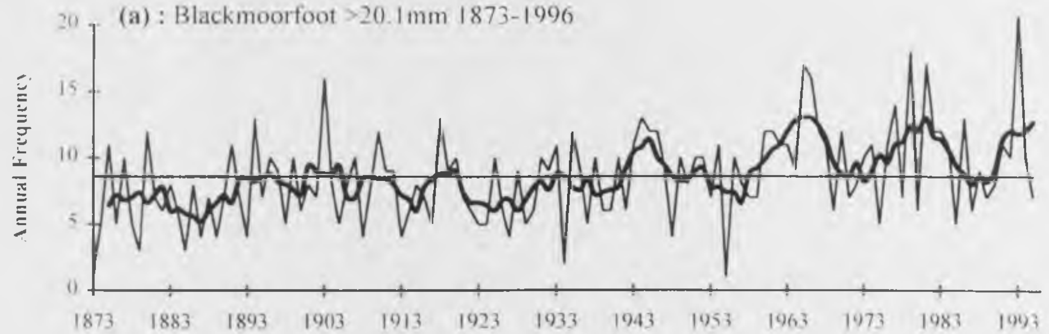
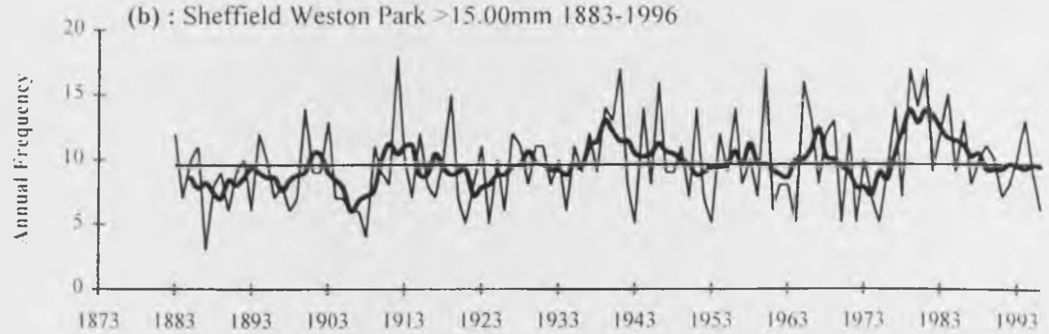
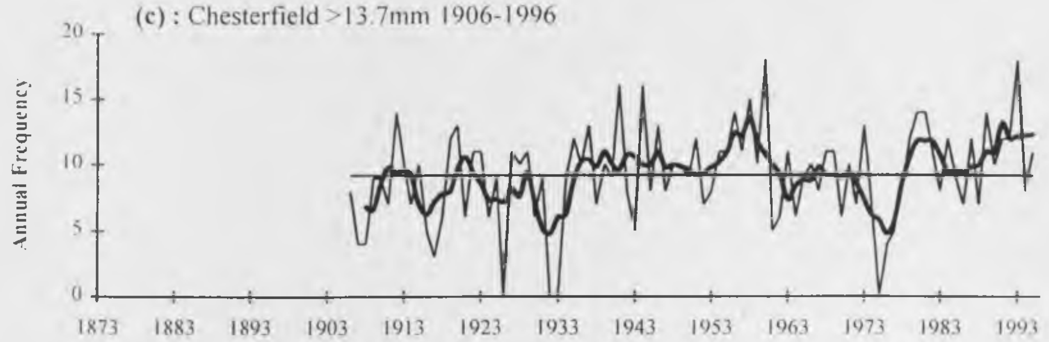
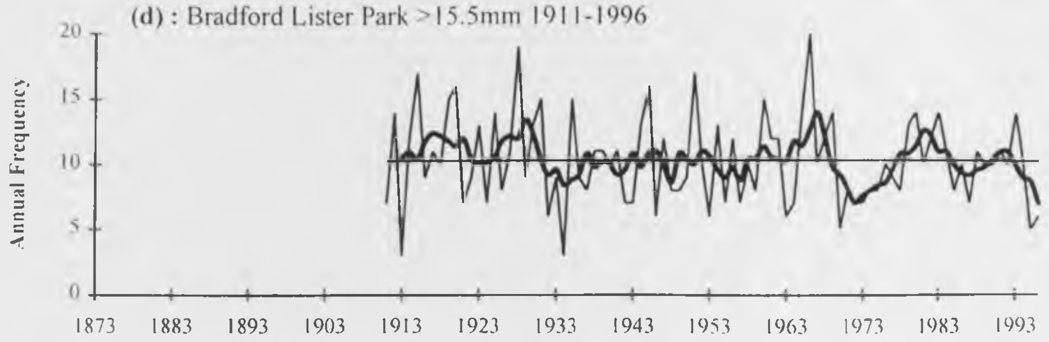


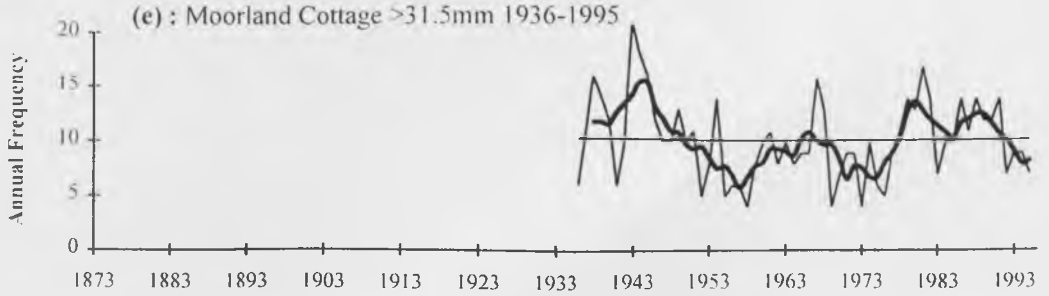
Figure 5.7 : Annual frequency of rainfall days over POT threshold


(a) : Blackmoorfoot >20.1mm 1873-1996


(b) : Sheffield Weston Park >15.00mm 1883-1996


(c) : Chesterfield >13.7mm 1906-1996


(d) : Bradford Lister Park >15.5mm 1911-1996


(e) : Moorland Cottage >31.5mm 1936-1995

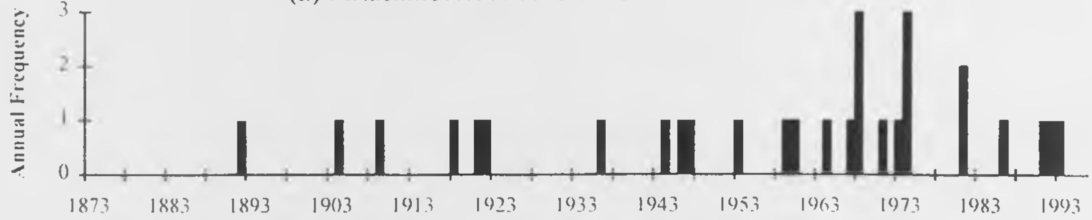
a decline at Moorland Cottage and Blackmoorfoot which reach a low in the mid-1950s, again over this period there appears to be little variation at Sheffield Weston Park and Bradford Lister Park, although there is a peak in frequencies at Chesterfield. The rainfall series appear to exhibit more common trends after the 1950s, when for example, there was a peak in the mid-1960s (a period of high flood frequency and magnitude) particularly pronounced at Blackmoorfoot. This was followed by a decline in the late-1960s to mid-1970s (a period of low flood frequency and magnitude), and a peak in frequencies between the late-1970s and mid-1980s (a period of high flood frequency and magnitude). There has been variation between sites in the 1990s with a decline in heavy rainfall frequency at Sheffield Weston Park, Bradford Lister Park and Moorland Cottage, and a rise in frequencies at Blackmoorfoot and Chesterfield. These rainfall POT series indicate that there is a complex pattern of variation in heavy daily rainfalls, when often trends apparent in one record will not appear in another. Clearly, this type of analysis would benefit greatly by the inclusion of more long-term rainfall records which may be available at the Met Office archive, however the time constraints of this project only allowed for discovery, collection and processing of a relatively small number of sites.

5.2.5.2. Rainfall over various thresholds

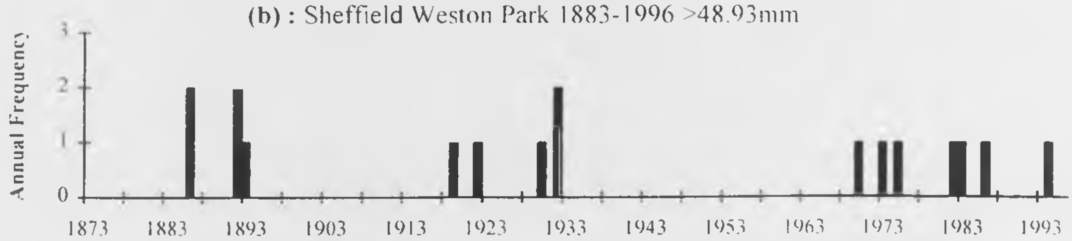
Thresholds for the 5-year (M_5) and 20-year (M_{20}) rainfall events have been calculated using the POT model described in section 4.2.3. and annual frequencies of daily rainfalls above this threshold plotted in figures 5.8 and 5.9 This technique allows for the investigation of the incidence of heavy daily rainfalls at a number of sites based on a common return period. A similar method was employed for investigating the timing of specific flood magnitudes in section 4.2.4.5. and it was found that the timing of high magnitude floods is often synchronous. This does not appear to be the case with heavy rainfall, the pattern is much more random and complex with significant variations in the timing of heavy rainfall days between sites. This may be due to the fact that rainfall totals can vary markedly over relatively short distances (Gregory, 1993), and the fact that return periods have been calculated over different length of records must also be considered.

In figure 5.8 the annual frequency of rainfall above the five year return period threshold shows that at Blackmoorfoot there appears to have been an increase in the incidence of rainfall events since the 1950s with particularly high frequencies in the mid-1960s to early-1970s (coinciding with a period of high flood frequency and magnitude). These trends do not appear to relate to any of the other records, at Sheffield Weston Park a series of events are recorded in the 1880s-1890s, 1920s-1930s and from the mid-1970s onwards. At Moorland Cottage groupings occur

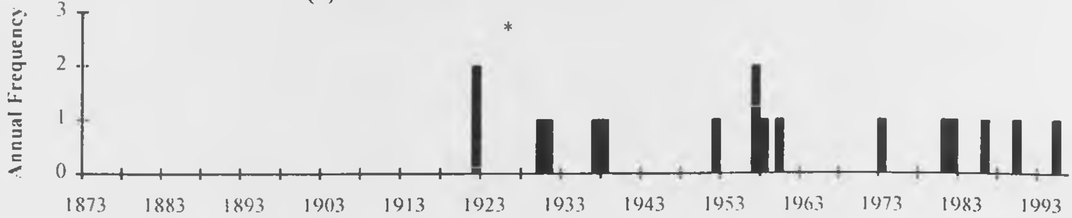
*Figure 5.8 : Heavy daily rainfall - Annual frequency of rainfall days > M , * start of record*



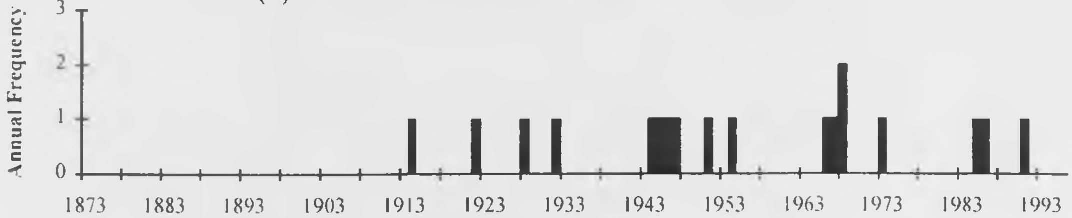
* **(a)** : Blackmoorfoot 1873-1995 >55.90mm



(b) : Sheffield Weston Park 1883-1996 >48.93mm



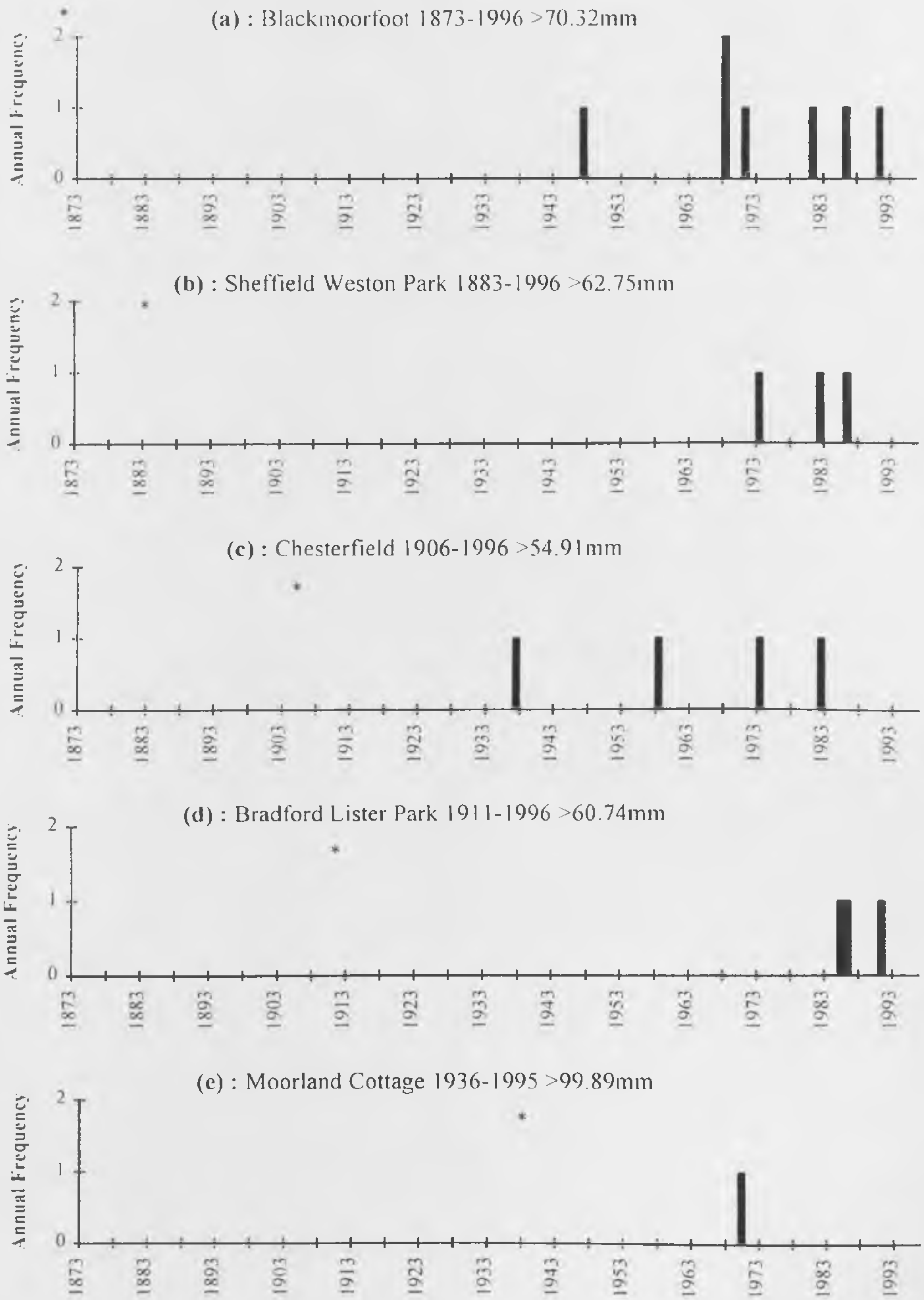
(c) : Chesterfield 1906-1996 >43.24mm



(d) : Bradford Lister Park 1911-1996 >47.55mm

(e) : Moorland Cottage 1936-1995 >83.02mm

*Figure 5.9 : Heavy daily rainfall - Annual frequency of rainfall days > M_{20} * start of record*



in the 1930s-1940s, mid-1960s and from the mid-1980s onwards. This large scale inter-site variation may suggest that this type of approach is limited when trying to explain trends in flood frequency and magnitude since the rainfall events being considered do not directly relate to individual flood events. However, figure 5.9 illustrates that when investigating higher return periods (20-years) interesting patterns can be established which can give an indication as to any general changes in the incidence of heavy rainfall. All the records in figure 5.9 suggest that heavy rainfalls have become more common since the 1960s, and particularly in the mid-1980s, again a period of high flood frequency and magnitude. Probably the main disadvantage of an approach such as this is that whilst general trends at an individual site may be illustrated, regional trends will not be evident since rainfall totals can vary markedly between stations on a particular day.

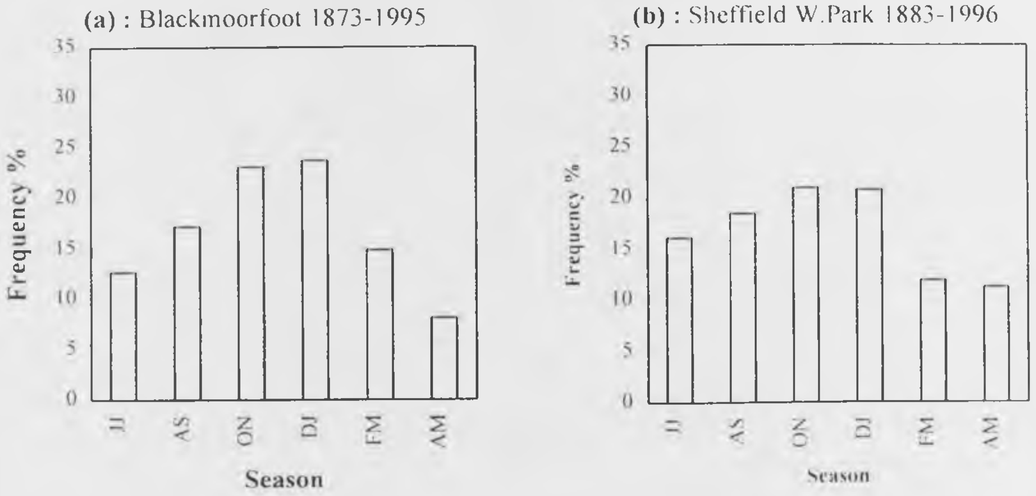
5.2.5.3. Seasonality of POT rainfall

Figure 5.10 shows 2-monthly frequencies of POT rainfall for each site. The highest frequencies tend to occur between October and January although frequencies are fairly high in all other seasons. This further illustrates the point that analysis of POT rainfall series will only give an indication of the general character variations in rainfall since clearly this rather uniform distribution of rainfall days throughout all seasons does not mirror that of flooding and therefore will not represent a series of rainfall days that generated floods. Inter-site variability is also further emphasised by table 5.2 (diagrams shown in appendix C) where M_{100} values have been calculated for each site using the POT model. When only five rainfall stations are being analysed, the highest 100-year rainfall estimated occurs in four different 2-monthly seasons, again illustrating inter-site variability which is not consistent with flood records where the majority of the largest Q_{100} estimates occurred in the February-March season.

5.2.6. Links between rainfall and flood series

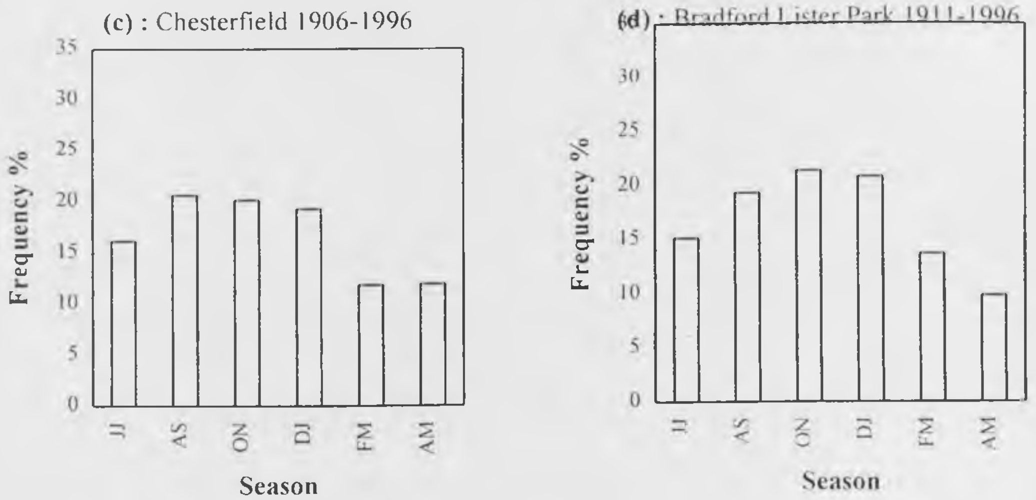
Records of annual rainfall and annual seasonal totals consider every day of rainfall over each year or season. POT rainfall records only consider those days above a specified threshold. Both techniques have their limitations when trying to establish links between these series and flood records. From the rainfall records examined in this study it is clear that these series cannot explain the majority of variation in the flood record. As would be expected, in particularly wet periods, with high annual and seasonal totals and a high incidence of POT rainfall events, flood frequency often tends to be higher. There is evidence of this in the mid-1960s and between the late-1970s and mid-1980s, when high POT frequencies and increased spring rainfall are associated with high flood frequency. Conversely, during particularly dry periods such as between the late-1960s and mid-1970s flood frequencies were particularly low.

Figure 5.10 : *2-monthly frequencies of POT rainfall expressed as a percentage of entire record JJ= Jun-Jul, AS=Aug-Sep, ON=Oct-Nov, DJ=Dec-Jan, FM=Feb-Mar, AM=Apr-May*



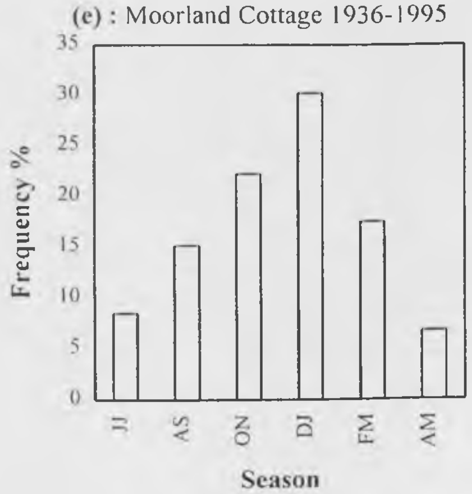
(a) : Blackmoorfoot 1873-1995

(b) : Sheffield W.Park 1883-1996



(c) : Chesterfield 1906-1996

(d) : Bradford Lister Park 1911-1996



(e) : Moorland Cottage 1936-1995

Table 5.2 : *Seasonal 100-year rainfall in mm and growth factors M_{100}/M_5 for each site (POT). Highest 100-year rainfall shown in bold, and lowest in italics.*

(a) : Blackmoorfoot 1873-1995

Season	**M_{100}**	**M_5**	**Growth Factor M_{100}/M_5**
Jun-Jul	66.64	37.73	1.771
Aug-Sep	65.89	38.67	1.704
Oct-Nov	68.44	41.07	1.666
Dec-Jan	**70.57**	42.14	1.675
Feb-Mar	66.86	38.66	1.730
Apr-May	*56.81*	32.42	1.753

(b) : Sheffield Weston Park 1883-1996

Season	**M_{100}**	**M_5**	**Growth Factor M_{100}/M_5**
Jun-Jul	**71.31**	38.43	1.856
Aug-Sep	60.45	34.16	1.769
Oct-Nov	48.06	29.35	1.637
Dec-Jan	*42.75*	27.05	1.581
Feb-Mar	48.41	27.86	1.737
Apr-May	56.43	31.06	1.817

(c) : Chesterfield 1906-1996

Season	**M_{100}**	**M_5**	**Growth Factor M_{100}/M_5**
Jun-Jul	**66.61**	35.77	1.862
Aug-Sep	53.51	30.74	1.741
Oct-Nov	47.75	28.20	1.694
Dec-Jan	46.06	27.35	1.684
Feb-Mar	*39.79*	23.32	1.706
Apr-May	42.00	24.23	1.734

(d) : Bradford Lister Park 1911-1996

Season	**M_{100}**	**M_5**	**Growth Factor M_{100}/M_5**
Jun-Jul	59.29	33.37	1.777
Aug-Sep	**65.47**	37.17	1.763
Oct-Nov	50.49	30.97	1.630
Dec-Jan	48.19	29.97	1.608
Feb-Mar	*46.07*	27.52	1.674
Apr-May	48.40	27.69	1.748

(e) : Moorland Cottage 1936-1995

Season	**M_{100}**	**M_5**	**Growth Factor M_{100}/M_5**
Jun-Jul	*74.31*	45.59	1.630
Aug-Sep	93.19	56.95	1.636
Oct-Nov	112.29	68.12	1.648
Dec-Jan	97.78	64.26	1.521
Feb-Mar	**116.15**	67.47	1.721
Apr-May	94.45	52.80	1.789

However throughout much of the instrumental period there appears to be no obvious links between rainfall series and variations in the flood record For example the late-nineteenth century was a period of high flood frequency and magnitude, but there is little evidence of increased POT rainfall events in the Yorkshire area at this time

The main problem with analysis of rainfall records is that many days are considered that do not directly influence flood events. To understand the direct controls of relationships between climate and floods, the period directly prior to each flood event must be studied, particularly in terms of the synoptic conditions which carried the precipitation and ultimately 'triggered' or 'generated' the flood event. It is only by an approach such as this that we can move away from generalising long-term climate and flood relationships, and establish the direct causal mechanisms which control flood frequency and magnitude.

5.3. VARIABILITY OF SNOWFALL 1875-1995 AND LINKS WITH FLOOD SERIES

The importance of snowmelt with respect to flooding in northern England has been discussed by several authors (e.g. Johnson & Archer, 1972; Jackson, 1978; Archer, 1981), with snowmelt producing some of the largest flood events on record in the Ouse basin (e.g. 1947 and 1982). However, determining the long-term variations in snowfall occurrence and amount in the UK, is difficult due to the lack of long records (Jones *et al.*, 1997). The longest record available for the UK was compiled by Jackson (1976), and was based on the earlier work of Bonacina (e.g. Bonacina, 1927; 1936; 1948; 1955) who classified each winter between 1875-6 and 1974-5 according to definitions ranging from 'very snowy' to 'little'. This work has been updated from 1978-9 to 1994-5 by Jones *et al.* (1997), and can be used to give a general indication of long-term variability over a similar timescale to some of the detailed flood records.

Figure 5.11 *: Snowy winter classification for 1875-6 and 1994-5 : (top) overall winter rating on the four-category scale, and (bottom) the number of the months classified as snowy per winter (from Jones et al., 1997)*

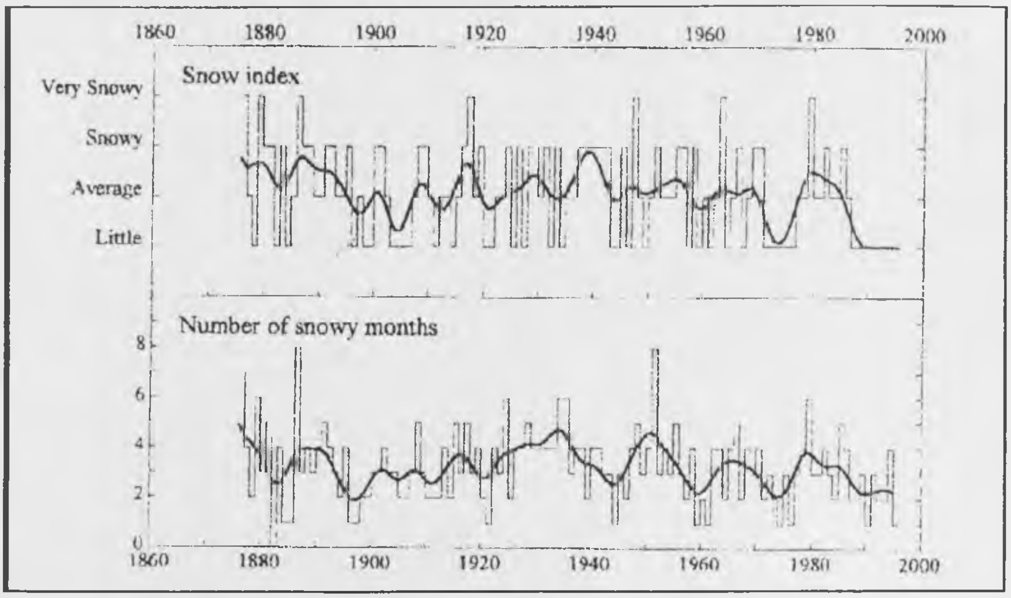
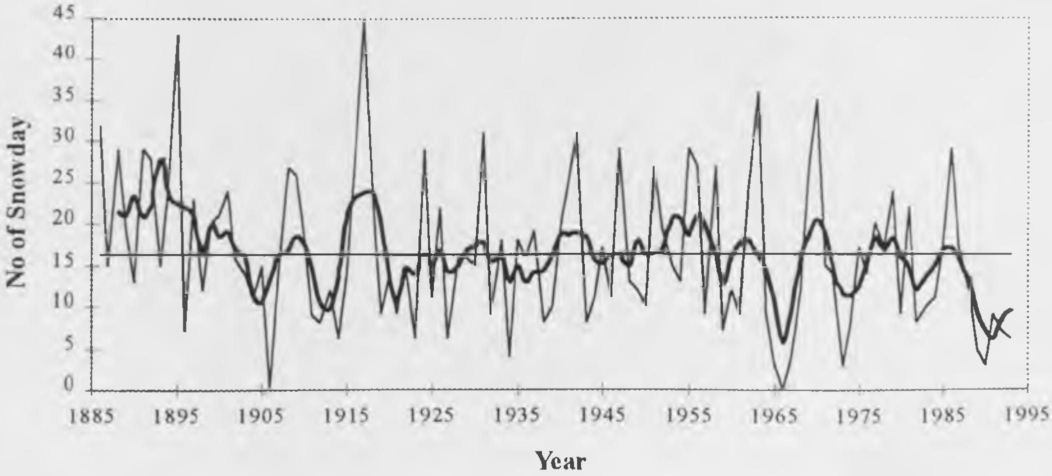


Figure 5.11 shows the summary of Bonacina's work by Jones *et al.* (1997). The authors suggest that the most widespread and snowiest winters on record are those of 1875-76, 1878-79, 1885-6, 1916-17, 1946-47, 1962-63 and 1978-79. Furthermore there has been a significant lack of 'snowy' winters since the mid-1980s, with the years between 1986-7 and 1994-5 all being classified as having 'little' snow. The frequency of snowy months was relatively high in the late nineteenth century and declined over the period 1900 to around 1915. Further peaks in the number of snowy months occurred in the mid-1930s, around 1950, the mid-1960s, and the mid-1980s. These peaks all coincide to some extent with peaks in flood magnitude, however

this link is very tentative since this record represents the UK as a whole, and the extent of regional variations in unclear.

One of the main problems when attempting to investigate the role of snow in flood generation over the historic timescale is that data are often summarised on a monthly or 'winter' basis and therefore do not allow detailed analysis of snow depth immediately prior to flood events. Several snow records for the Ouse basin have been published in the annual *Snow Survey of Great Britain*, however the resolution of data varies from daily snow depth at Huddersfield (Oakes) between 1968 and 1977, to monthly statistics for all other stations. Since these records are relatively short and cover a period of low flood frequency and magnitude it was decided not to include these data in this study. Longer-term records of the number of snowdays at York between October and March exist between 1886 and 1993, and have been published on an annual basis by the Yorkshire Philosophical Society. This series is shown in figure 5.12 and exhibits some of the trends suggested by Jones *et al.* (1997). It appears that the incidence of snowdays was generally high in the late nineteenth century and declined from the turn of the century until around 1915. The winter of 1916-17 shows a particularly high number of snowdays (as suggested by Jones *et al.*, 1997), however, between 1925 and 1960 the 5-year running mean shows little variation. The 1960s were characterised by extremely high and low totals, whereas from the 1970s until the mid-1980s there is little variation about the mean. Since the mid-1980s the number of snowdays has declined dramatically.

***Figure 5.12** : Winter (October-March) snowdays at York 1886-1993. Compiled from annual reports of the Yorkshire Philosophical Society*



5.4. FLOOD GENERATING ATMOSPHERIC CIRCULATION TYPES

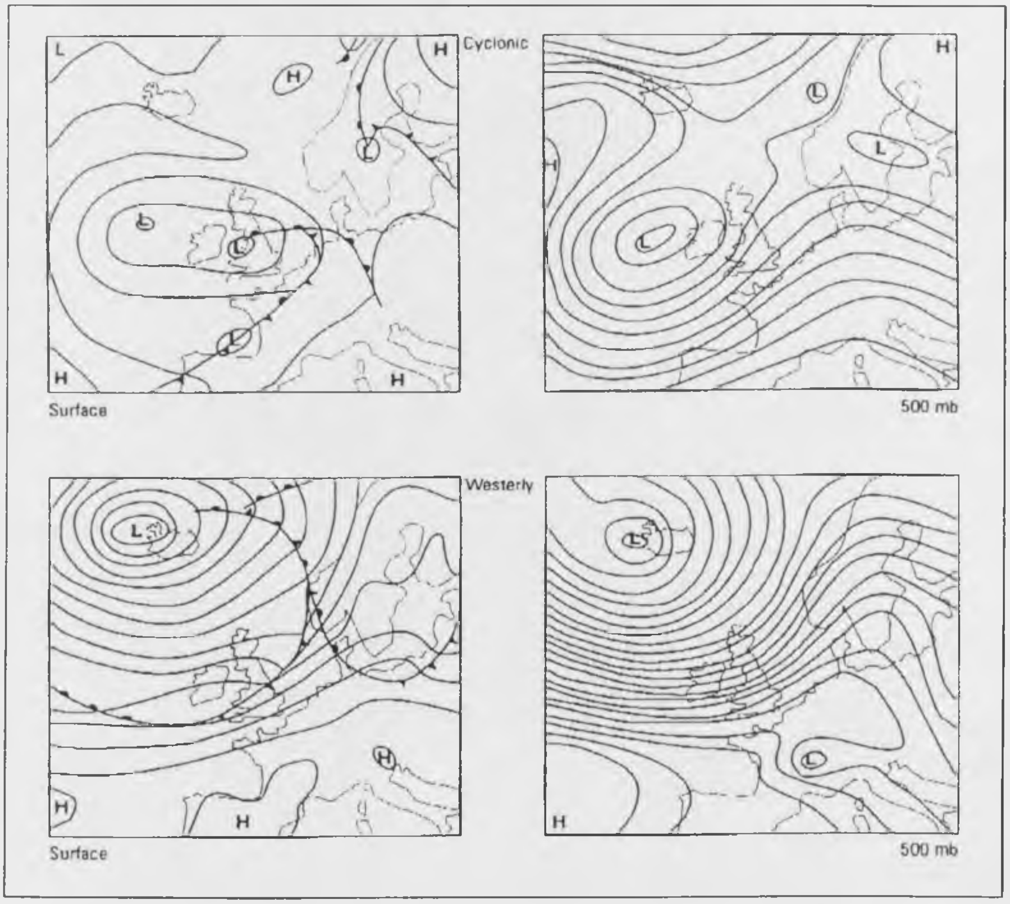
5.4.1. Introduction

The next stage in attempting to link climate to observed variations in flood frequency, magnitude and seasonality is to investigate the causal mechanisms of individual flood events. The climate of the UK is controlled by atmospheric circulation patterns, and these have been classified on a daily basis into 27 different types by Lamb (1972) (see section 2.3.2.1) (Examples of surface and 500mb charts for two of the most common types, cyclonic and westerly, are shown in figure 5 13). The record covers the period 1861 to 1995 and therefore encompasses the entire period of gauged flood records in the Ouse basin By identifying the synoptic causes of flood events through analysis of circulation types immediately prior to floods, a detailed picture of flood generation can be established One of the only studies in the UK to take such a detailed approach is that of Grew (1996) who identified circulation types responsible for flood generation in Scotland. She found that three main types commonly 'triggered' floods; cyclonic, westerly and south-westerly, and that the dominance of a particular type is heavily dependent on the geographical location of catchments Flood series from the west of Scotland were found to be dominated by floods generating under westerly and south-westerly synoptic situations, whereas floods on the east of Scotland were shown to be more influenced by cyclonic circulation types.

Grew (1996) classified flood events based on the circulation type on the day of flood and the preceding day. Primary (most frequent flood generating type) and secondary circulation types were identified for each site on each day. In this study a slightly different approach has been taken, whereby each flood event is classified on the basis of the circulation type which delivered the majority of precipitation prior to the event. Using circulation types alone it is difficult to determine the period over which climatic conditions have been important prior to a flood. Therefore it is hoped that by the incorporation of daily rainfall records, those days directly responsible for flood generation can be identified more clearly, and classified more accurately.

The main aim of this section is to identify circulation types that are important for flood generation in the Ouse basin and to establish whether variations in the annual and seasonal frequencies of these types can explain the observed patterns in flood frequency, magnitude and seasonality.

***Figure 5.13** : Typical examples of cyclonic and westerly Lamb circulation types, shown on surface and 500mb charts (redrawn from Lamb, 1972).*



5.4.2. Method for determining dominant flood generating circulation types

To identify those circulation types important for flood generation each POT flood event has been classified as being caused by one individual circulation type by the following method. Records of daily rainfall were used to establish the specific days prior to each flood event which provided the majority of precipitation input. The daily rainfall records were chosen for each POT flood site based on proximity to the tributary being considered. Preference was given to upland raingauges since these tend to receive higher amounts of rainfall, and therefore would make the task of distinguishing the important days more straightforward. Problems arose with some of the longer flood records such as the Ouse at York where the flood record extends to 1878 whereas the longest upland rainfall record in the area, Moorland Cottage, only dates to 1936. In this case the longer rainfall records (such as Blackmoorfoot) had to be used prior to records at Moorland Cottage. However, by overlapping a common period in both rainfall records it was found that there was a good relationship between the sites on days of heavy rainfall prior to flood events. A list of which raingauges were used for a particular POT flood record is given in table 5.3, and their location shown in figure 5.1.

Table 5.3 : Raingauges used in flood generating circulation analysis

Station Name	Grid Ref	Length of Record	POT record Analysed
Arkengarthdale	NY 990 030	1971-1995	Swale
Blackmoorfoot Reservoir	SE 096 130	1873-1982	Ouse, Aire, Don
Chesterfield S.Works N	SK 391 742	1980-1996	Don
Chesterfield S.Works	SK 392 746	1906-1979	Don
Silsden Reservoir	SE 044 475	1961-1996	Aire
Birdsall House	SE 818 651	1907-1995	Derwent
Lower Barden Reservoir	SE 035 563	1961-1995	Wharfe
Moorland Cottage	SD 807 923	1936-1995	Ouse, Swale, Ure, Wharfe, Nidd

In order to capture the days of rainfall directly responsible for flood generation, a maximum number of days prior to each flood event had to be set. A maximum of four days prior to the flood day was chosen (five days in all including day of flood), primarily due to the large size of some of the catchments and the fact that any longer duration may reflect antecedent conditions and not precipitation events directly responsible for the flood. This is not to suggest that antecedent conditions are not important in flood generation, they clearly are, this approach is attempting to simplify a very complex situation. The next stage was to define a minimum threshold of daily rainfall, so as to only consider those days with a significant volume of rain. An arbitrary minimum value of 10mm of rainfall per day was taken for all raingauges. The rainfall totals on each day greater that 10mm on the four days of rainfall prior to the event and the rainfall on the day of flood were then weighted using the following formula :

$$\text{Weighting} = (\text{Daily rainfall - Rainfall threshold})^2$$

In this case the rainfall threshold is 10mm. This gives a greater emphasis to those days with high rainfall totals. The circulation types corresponding to the rainfall days were then assigned the weighting value, and a total weight calculated for each circulation type involved in a particular flood event. The circulation type with the highest weighted value was then taken as the dominant synoptic type which generated that particular flood event. This process was repeated for each POT flood event at each site using an EXCEL macro

Limitations of the method

When trying to simplify an inherently complex situation assumptions must be made, and in doing so can often introduce limitations into the results of a study. In this case there are a number of limitations which need to be considered prior to interpretation of results

1. Each flood event is classified as being generated by one individual circulation type, whereas in reality two or more types can combine to produce a flood event. However on examination of the raw data it became clear that the majority of flood events were generated by one dominant type which usually persisted over a number of days prior to the flood event.

2. POT flood events at each flood gauging site are classified using only one, or sometimes two, daily rainfall records. It may be suggested that this will be unrepresentative of rainfall over the whole catchment.

3. Using this technique some flood events were not classified due to a particularly low weighting value (i.e. very low rainfall input). This may add weight to the case for using a more detailed raingauge network, or may relate to pure snowmelt flood events with little or no rainfall input. The number of unclassified floods at each site is shown in table 5.4

4. Finally, limitations of the Lamb catalogue itself may influence the results of this study since the circulation patterns are classified on a UK scale, are their applicability to such a regional study may be questionable. A regional classification of airflow types such as that of Mayes (1991) may yield more relevant results, although as yet airflow types have not been classified for this area.

Table 5.4 : Number of unclassified floods at each site in flood generating circulation analysis

Flood Site	**Total No of POT floods**	**No of POT floods unclassified**	**Percentage of POT floods unclassified**
Ouse at York	252	11	4.37
Don at Doncaster	164	18	10.98
Nidd at Hunsingore	242	26	10.74
Wharfe at Flint Mill	215	11	5.12
Swale at Crakehill	171	6	3.51
Ure at Westwick	169	8	4.73
Aire at Armley	122	17	13.93
Derwent at Buttercrambe	119	14	11.76

5.4.3. Flood generating circulation types in the Ouse basin

Once each POT flood event has been classified the next stage is to identify the most important circulations that generate floods Table 5.5 shows the percentage and rank of POT floods generated by each individual circulation type at each gauging site. A cumulative percentage for each circulation type is also given, which is the sum of percentages at all sites and gives an indication of those circulations that are important for basin wide flood generation. The four most common circulation types that generate floods have been highlighted in table 5.5. they are cyclonic, westerly, cyclonic-westerly and south-westerly respectively, and account for 78.25% of all POT floods at the eight sites considered. Cyclonic and westerly types are by far the most important flood generating circulations, and are ranked as either 1 or 2 at all sites. The rank of cyclonic-westerly ranges between 3 and 5, whereas the rank of south-westerlies ranges between 3 and 10 showing that the importance of this type as a flood generator can vary markedly between sites. South-westerlies appear to be far less important on the Derwent (rank = 8) and the Don (rank = 10) which may be due to their geographical location. On the Don at Doncaster cyclonic-easterly (rank = 3) and easterly (rank = 4) circulations are important flood generating types, although the overall percentage of floods generated by these types on the Don is still relatively low (10.27%). Floods that are generated under cyclonic conditions account for 49.32% of POT events on the Don, the highest value at any of the eight sites. This high dominance of cyclonics and the influence of cyclonic-easterly and easterly circulations is probably due to its location in the south-eastern part of the Ouse basin. Similarly the Derwent, which is situated in the north-easterly part of the catchment also shows cyclonic circulations to be of disproportionate importance, cyclonics generate 40.00% of POT events on the Derwent at Buttercrambe, whereas westerlies, the second most important type only generates 13.33% of

Table 5.5 : *Percentage of floods caused by individual circulation types at each site. Highlighted rows show four most common circulation types that generate floods.*

Circulation Type	Ouse	Rank	Don	Rank	Nidd	Rank	Wharfe	Rank	Swale	Rank	Ure	Rank	Aire	Rank	Derwent	Rank	Cumulative %	Rank
U	2.49	7	2.05	9	2.34	6	0.99	9	1.82	8	1.86	6	1.90	8	4.76	5	18.21	7
A	0.83	12	0.68	16	0.93	11	0.49	13	-	-	-	-	-	-	3.81	7	6.75	15
ANE	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.95	15	0.95	21
AE	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ASE	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
AS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ASW	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
AW	0.41	15	-	-	-	-	1.48	8	1.21	10	1.24	8	0.95	10	-	-	5.30	17
ANW	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
AN	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NE	0.83	13	-	-	0.47	15	-	-	0.61	14	0.62	11	-	-	0.95	16	3.48	19
E	0.41	16	4.11	4	0.93	12	0.49	14	1.21	11	-	-	1.90	9	1.90	11	10.97	11
SE	0.83	14	2.74	7	0.47	16	-	-	1.21	12	0.62	12	-	-	0.95	17	6.82	14
S	3.73	5	2.74	8	5.14	4	1.97	5	5.45	4	1.86	7	0.95	11	5.71	3	27.57	5
SW	5.81	4	2.05	10	3.74	5	3.94	4	5.45	5	8.07	4	5.71	3	3.81	8	38.60	4
W	32.78	1	14.38	2	29.44	2	40.39	1	24.24	2	36.02	1	24.76	2	13.33	2	215.36	2
NW	1.24	10	0.68	17	0.93	13	1.97	6	2.42	6	3.11	5	3.81	6	0.95	18	15.13	8
N	1.24	11	1.37	12	0.47	17	0.99	10	1.21	13	-	-	-	-	1.90	12	7.18	13
C	31.54	2	49.32	1	39.25	1	33.00	2	38.18	1	31.68	2	44.76	1	40.00	1	307.73	1
CNE	0.41	17	0.68	18	-	-	-	-	0.61	15	-	-	0.95	12	0.95	19	3.61	18
CE	1.66	9	6.16	3	1.40	9	-	-	0.61	16	-	-	2.86	7	1.90	13	14.59	9
CSE	-	-	1.37	13	-	-	-	-	-	-	-	-	0.95	13	-	-	2.32	20
CS	0.41	18	2.05	11	1.40	10	0.49	15	0.61	17	0.62	13	-	-	2.86	9	8.45	12
CSW	2.90	6	1.37	14	2.34	7	0.99	11	1.82	9	1.24	9	-	-	2.86	10	13.51	10
CW	9.54	3	3.42	5	7.94	3	9.85	3	10.30	3	11.80	3	5.71	4	5.71	4	64.30	3
CNW	0.41	19	1.37	15	0.93	14	0.99	12	0.61	18	-	-	-	-	1.90	14	6.22	16
CN	2.49	8	3.42	6	1.87	8	1.97	7	2.42	7	1.24	10	4.76	5	4.76	6	22.94	6

flood events Also unusual at this site is that southerly circulations are ranked as being the third most important flood generating type.

In general all other sites have Pennine headwaters and show the same circulation types to be important in flood generation However the most dominant type varies between cyclonic and westerly, for example, even catchments which are in close proximity can show this variation, the Ure at Westwick suggests that westerlies are the dominant flood generating type, whereas on the Swale at Crakehill cyclonics are more important. Overall it is clear that a relatively small number of circulation types generate the majority of floods in the Yorkshire area, these being cyclonic, westerly, cyclonic-westerly and south-westerly.

5.4.3.1. Weather associated with dominant flood generating circulation types

To answer the question as to why a small number of circulation types control flood generation in the Ouse basin we must consider the relationships between circulations and the weather associated with them, particularly precipitation. Cyclonic circulation types have been identified as being the most important flood generating type in the Yorkshire Ouse area. The weather associated with the cyclonic type is often wet and disturbed (Lamb, 1972), however, one of the main features with direct relevance to flood generation in the eastern part of the UK, is that there is an absence of a marked west-east precipitation gradient (O'Hare & Sweeney, 1993). Due to the considerable variability of depression tracks over long periods, cyclonics tend to produce a fairly uniform distribution of precipitation over the British Isles (Sweeney & O'Hare, 1992). This combined with the fact that cyclonics are one of the most frequently occurring circulation types (occurred 12.8% of the times between 1880-1980 (Sweeney & O'Hare, 1992)) causes cyclonics to be proportionately more important than westerly circulation in flood generation in the Ouse basin. Westerly circulations are generally associated with unsettled or changeable weather, with the majority of rain falling the northern and western parts of the British Isles (Lamb, 1972). There is a marked west-east precipitation gradient associated with westerly type, with a prominent rain shadow to the east of the Pennines (Sweeney & O'Hare, 1992). Despite this it is clear that westerly circulation types play an important role in flood generation in the Ouse basin, which may reflect the fact that the majority of tributaries have headwaters in the Pennines, which do receive high rainfall totals from westerly circulations. The influence of westerly type diminishes in the most easterly catchments in the basin, the Don and Derwent, illustrating the rain shadow effect in easterly situations. In general terms westerly circulations occurred 18.9% of the time between 1880 and 1980 (Sweeney & O'Hare, 1992), and is the most frequently occurring circulation type in the Lamb catalogue.

Two other circulation types have been identified as being important, albeit to a lesser extent, for flood generation in the Ouse basin, cyclonic-westerly and south-westerly type The annual frequencies of these types are much lower than those examined previously, cyclonic-westerlies occurred 4.0% of the time between 1880 and 1980 and south-westerlies 2.6% of the time (Sweeney & O'Hare, 1992). Cyclonic-westerlies tend to yield high rainfall totals and the west-east contrast is not as high as with pure westerly circulations, resulting in proportionately more rainfall falling in eastern parts of the country. The influence of south-westerlies in flood generation again relates to the simple fact that high precipitation totals are common with this type, although there is a marked west-east contrast in rainfall receipts. South-westerlies are warm, moist airmasses and have been shown to trigger snowmelt flood events at a number of locations (e.g. Jackson, 1978; Marsh & Monkhouse, 1991). If a catchment is snow covered and then a warm south-westerly circulation moves in to dominate the country, the associated rise in temperature may cause a thaw. If this is combined with rainfall, large flood events may result, indeed evidence for large snowmelt floods occurs throughout the historic record with a notable example in 1614 at York. It is therefore suggested that this circulation type is a particularly important flood generating type which may generate high magnitude flood events given the right antecedent conditions.

On the Don at Doncaster cyclonic-easterly circulations were shown to be of some importance in flood generation. This type moves from east to west and delivers high precipitation totals particularly in southern England. Rainfall totals are still fairly high in eastern England but diminish as the weather type moves to the west.

5.4.3.2. Relationships between flood magnitude and generating circulation types

To investigate whether certain circulation types generate floods of a particular magnitude POT flood records at each site have been divided into magnitude categories defined as follows :

Minor flood : $\geq$ *standard threshold* $< Q_2$
Moderate flood : $\geq Q_2 < Q_{10}$
Major flood : $\geq Q_{10}$

The sub-divisions are somewhat arbitrary, though by using return periods to define magnitude categories, systematic inter-site comparisons can be made. The relationship between flood magnitude and generating circulation type is undoubtedly a complex one, therefore this approach simply attempts to examine the number of floods generated by each circulation type in each magnitude category. Tables 5.6 (a)-(c) shows the rank order of the number of POT

Table 5.6(a) : Number of ***'minor'*** *floods (>standard threshold $<Q_2$) generated by circulation types at each site*

Circulation Type	Rank	Ouse	Don	Nidd	Wharfe	Swale	Ure	Aire	Derwent	Total no of Floods	Total %
C	1	50	44	69	63	49	49	34	36	394	36.65
W	2	50	17	58	72	31	53	24	13	318	29.58
CW	3	15	5	16	18	16	18	5	5	98	9.12
SW	4	9	2	7	6	5	12	5	3	49	4.56
S	5	6	2	11	4	9	3	1	4	40	3.72
CN	6	5	1	4	3	2	2	4	3	24	2.23
NW	7	2	0	2	4	4	5	3	1	21	1.95
U	8	4	1	5	1	3	2	0	4	20	1.86
CE	=9	3	5	3	-	1	-	3	2	17	1.58
CSW	=9	4	2	5	1	2	1	-	2	17	1.58
E	=11	1	4	1	-	2	-	1	2	11	1.02
CS	=11	1	1	3	1	1	1	-	3	11	1.02
N	=13	2	1	1	2	2	-	-	2	10	0.93
CNW	=13	1	2	2	2	1	-	-	2	10	0.93
A	=15	2	1	1	1	-	-	-	4	9	0.84
AW	=15	1	-	-	3	2	2	1	-	9	0.84
SE	17	2	1	1	-	2	1	-	1	8	0.74
CNE	18	1	-	-	-	1	-	1	1	4	0.37
NE	=19	-	-	-	-	-	1	-	1	2	0.19
CSE	=19	-	1	-	-	-	-	1	-	2	0.19
ANE	21	-	-	-	-	-	-	-	1	1	0.09

Table 5.6(b) : Number of ***'moderate'*** *floods ($\geq Q_2 < Q_{10}$) generated by circulation types at each site*

Circulation Type	Rank	Ouse	Don	Nidd	Wharfe	Swale	Ure	Aire	Derwent	Total no of Floods	Total %
C	1	21	20	12	4	11	2	11	5	86	42.36
W	2	27	3	4	6	7	3	2	1	53	26.11
SW	3	4	1	-	2	3	1	1	1	13	6.40
CW	4	8	-	-	1	-	1	1	1	12	5.91
CN	5	1	4	-	-	2	-	1	-	8	3.94
S	=6	2	2	-	-	-	-	-	1	5	2.46
CSW	=6	2	-	-	1	-	1	-	1	5	2.46
U	8	1	2	-	-	-	-	1	-	4	1.97
NE	=9	2	-	-	-	1	-	-	-	3	1.48
E	=9	-	2	-	1	-	-	-	-	3	1.48
SE	=9	-	3	-	-	-	-	-	-	3	1.48
NW	=9	1	1	-	-	-	-	1	-	3	1.48
CE	13	-	2	-	-	-	-	-	-	2	0.99
N	=14	1	-	-	-	-	-	-	-	1	0.49
CNE	=14	-	1	-	-	-	-	-	-	1	0.49
CS	=14	-	1	-	-	-	-	-	-	1	0.49

Table 5.6(c) : *Number of* **'major'** *floods ($>Q_{10}$) generated by circulation types at each site*

Circulation Type	Rank	Ouse	Don	Nidd	Wharfe	Swale	Ure	Aire	Derwent	Total no of Floods	Total %
C	1	5	8	3	0	3	-	2	1	22	35.48
W	2	2	1	1	4	2	2	-	-	12	19.35
U	3	1	-	-	1	-	1	1	1	5	8.06
SW	=4	1	-	1	-	1	-	-	-	3	4.84
CE	=4	1	2	-	-	-	-	-	-	3	4.84
CW	=4	-	-	1	1	1	-	-	-	3	4.84
CN	=4	-	-	-	1	-	-	-	2	3	4.84
E	=8	-	-	1	-	-	-	1	-	2	3.23
S	=8	1	-	-	-	-	-	-	1	2	3.23
CSW	=8	1	-	-	-	1	-	-	-	2	3.23
A	=11	-	-	1	-	-	-	-	-	1	1.61
NE	=11	-	-	1	-	-	-	-	-	1	1.61
N	=11	-	1	-	-	-	-	-	-	1	1.61
CSE	=11	-	1	-	-	-	-	-	-	1	1.61
CS	=11	-	1	-	-	-	-	-	-	1	1.61

floods generated at each site by circulation types in the three magnitude categories. A total percentage of the frequency of floods generated by each circulation type at all sites is also given. Cyclonic and westerly types are by far the most important flood generators at all magnitudes, although significantly, the percentage of total floods generated by westerly circulations declines as magnitude increases, illustrating the importance of cyclonic type for flood generation at higher magnitudes

A number of other circulation types also appear to be important for flood generation, albeit to a lesser extent. Common generating types are unclassified, cyclonic-easterly, cyclonic-northerly and southerly. Unclassified circulations are ranked as the third most important flood generator at 'major' magnitudes, although still only account for 8.06% of floods of this magnitude. It is difficult to assess the reasons for this importance since several synoptic situations can be 'unclassified', such as when there are rapid changes in a twenty-four hour period, or circulation systems are relatively small (Lamb, 1972).

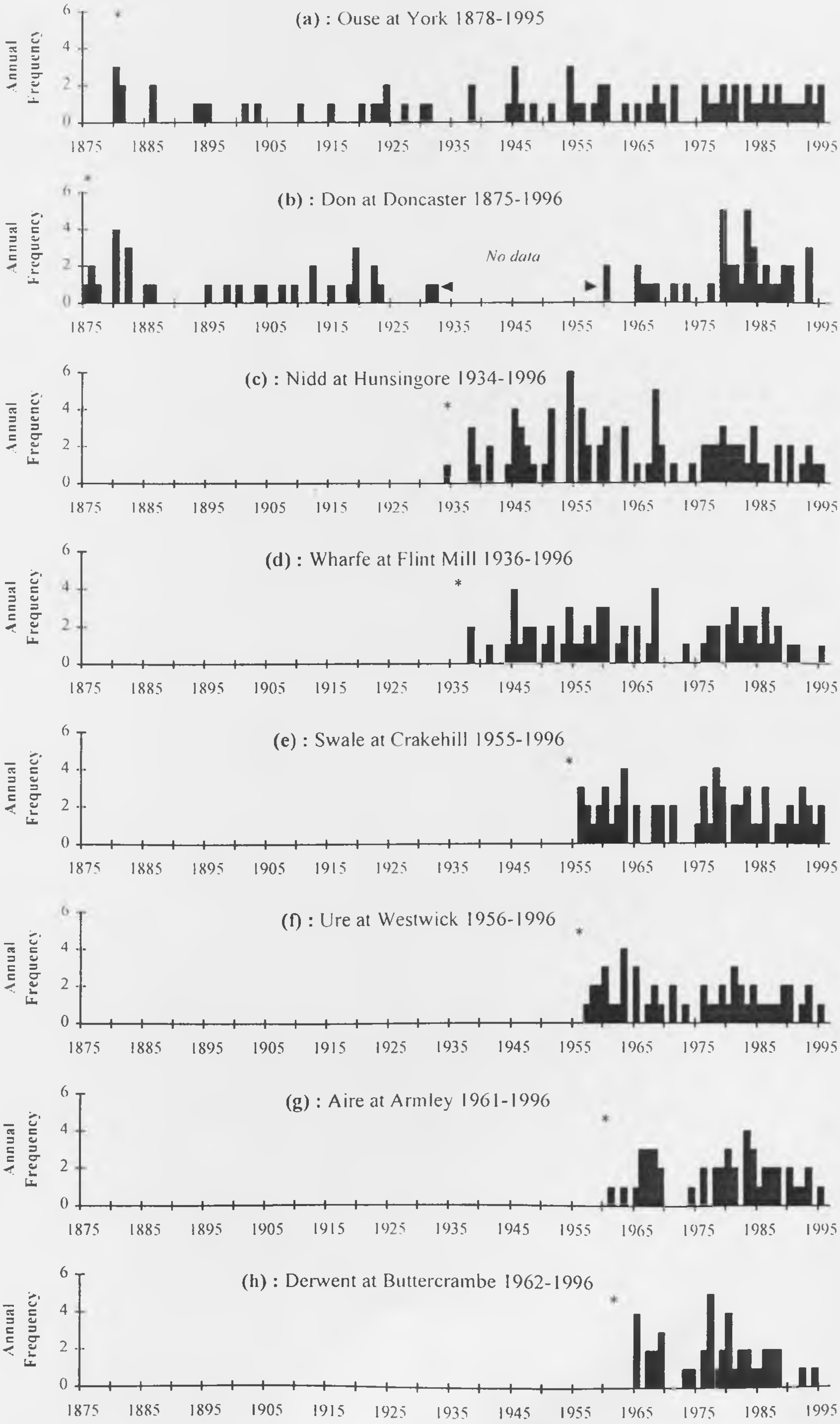
A different overall picture is again evident on the River Don, which shows that northerly, cyclonic-south-easterly and cyclonic-southerly circulation types generate at least one flood classified as being a major event. These types do not generate floods of this magnitude on any other tributary, although reasons for this are as yet unclear.

In summary there are four main circulation types that are particularly important for flood generation in the Ouse basin, namely cyclonic, westerly, cyclonic-westerly and south-westerly. Detailed analysis of variations with all of the 27 individual Lamb types would be both time consuming and may yield little in the way of explanation as to variations in flood frequency and magnitude. In the following sections temporal variations in floods generated by the four main circulation types are evaluated, and how the annual and seasonal frequencies of those circulation types has varied through time.

5.4.3.3 Temporal variation in the incidence of floods generated by individual circulation types

Four atmospheric circulation types have been identified that generate the majority of floods in the Yorkshire area, cyclonic, westerly, cyclonic-westerly and south-westerly. The frequency of floods generated over time by these types will obviously vary to some extent according to periods of high and low frequency identified in the POT flood records. The main aim of this section is to investigate whether flood generation in certain time periods has been dominated by

Figure 5.14 : Annual frequency of floods generated by **cyclonic** *circulations. * start of record*



(a) : Ouse at York 1878-1995

(b) : Don at Doncaster 1875-1996

(c) : Nidd at Hunsingore 1934-1996

(d) : Wharfe at Flint Mill 1936-1996

(e) : Swale at Crakehill 1955-1996

(f) : Ure at Westwick 1956-1996

(g) : Aire at Armley 1961-1996

(h) : Derwent at Buttercrambe 1962-1996

***Figure 5.15** : Annual frequency of floods generated by **westerly** circulations. * start of record*

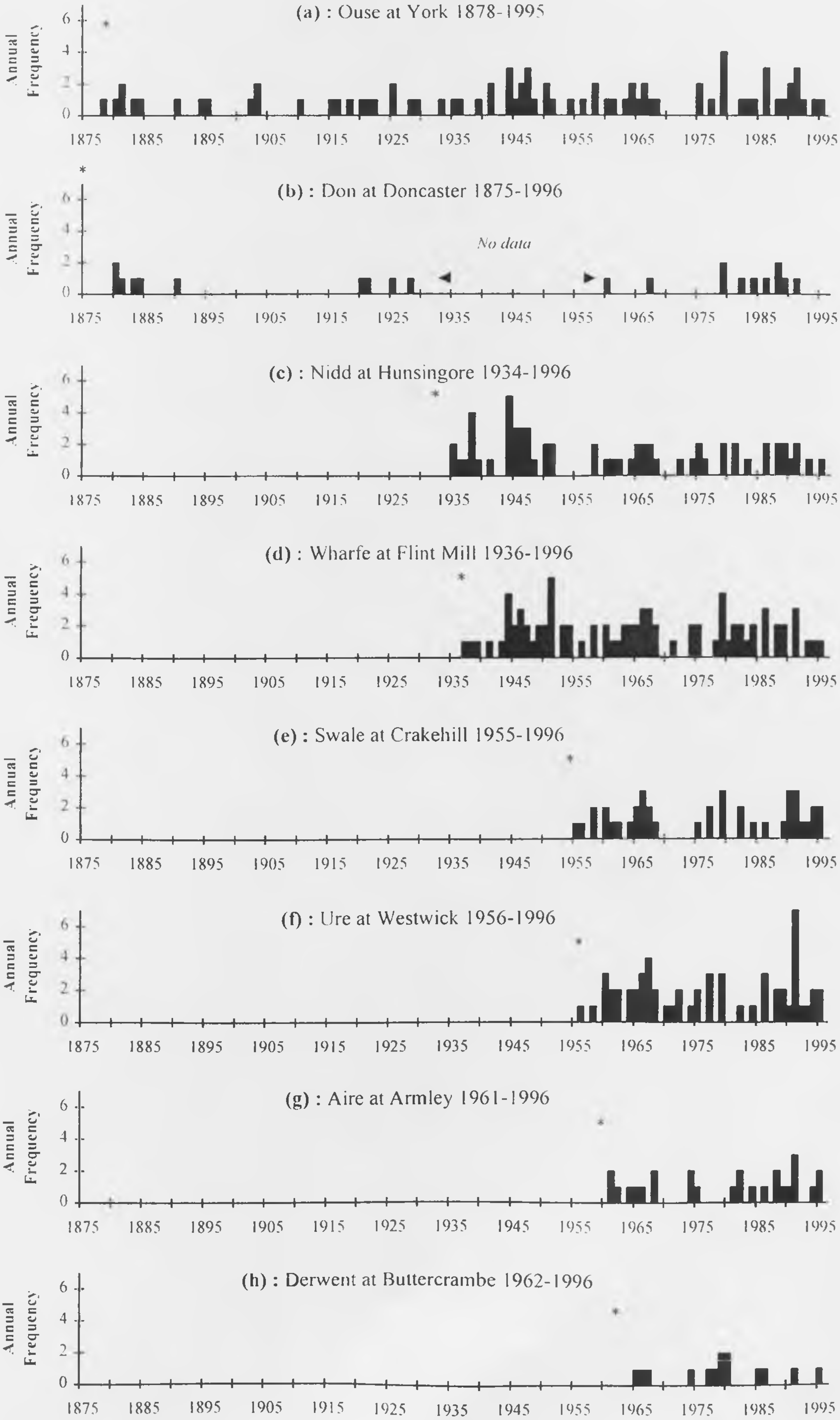
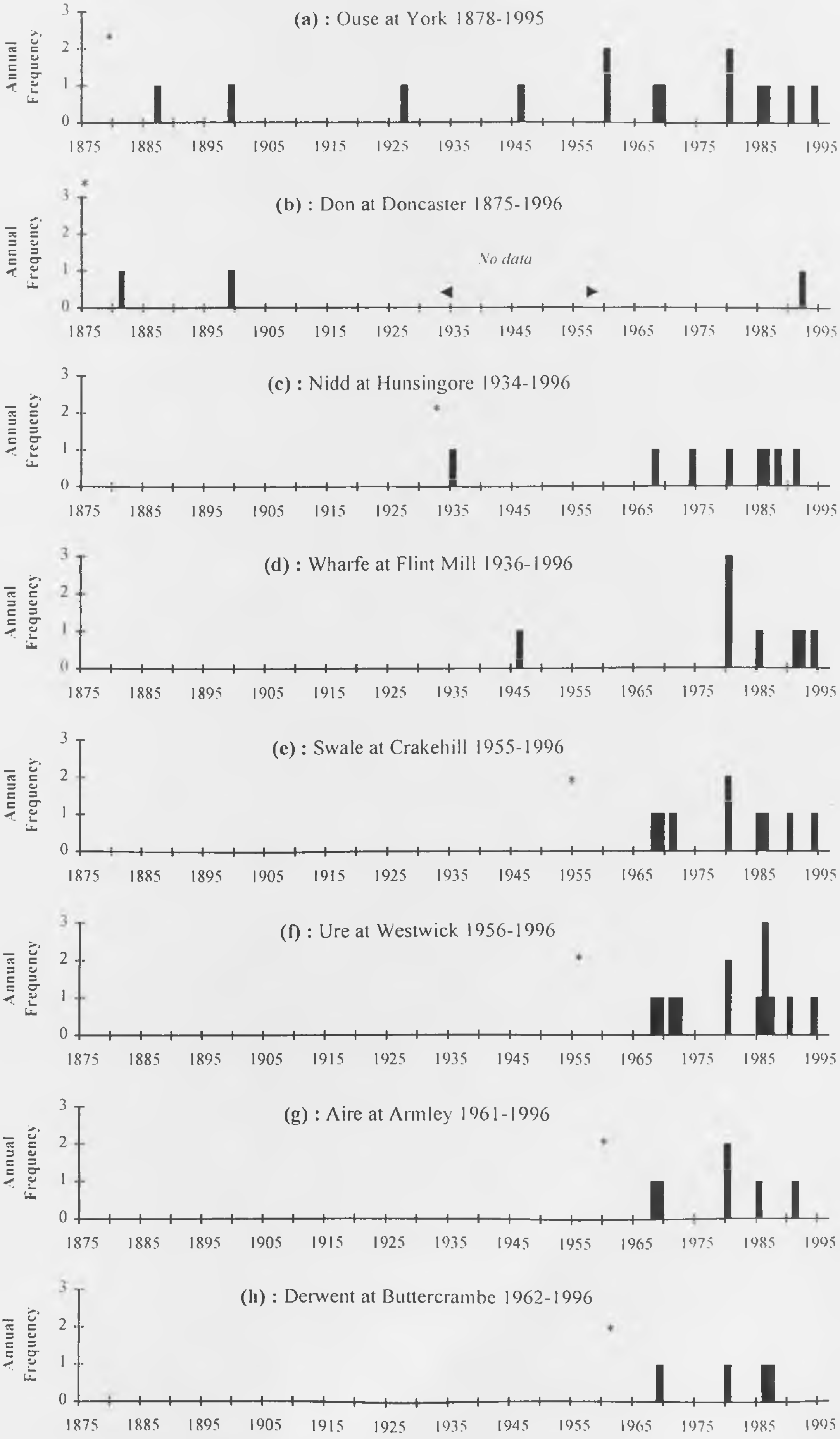


Figure 5.16 : Annual frequency of floods generated by ***south-westerly*** *circulations*
** start of record*



(a) : Ouse at York 1878-1995

(b) : Don at Doncaster 1875-1996

(c) : Nidd at Hunsingore 1934-1996

(d) : Wharfe at Flint Mill 1936-1996

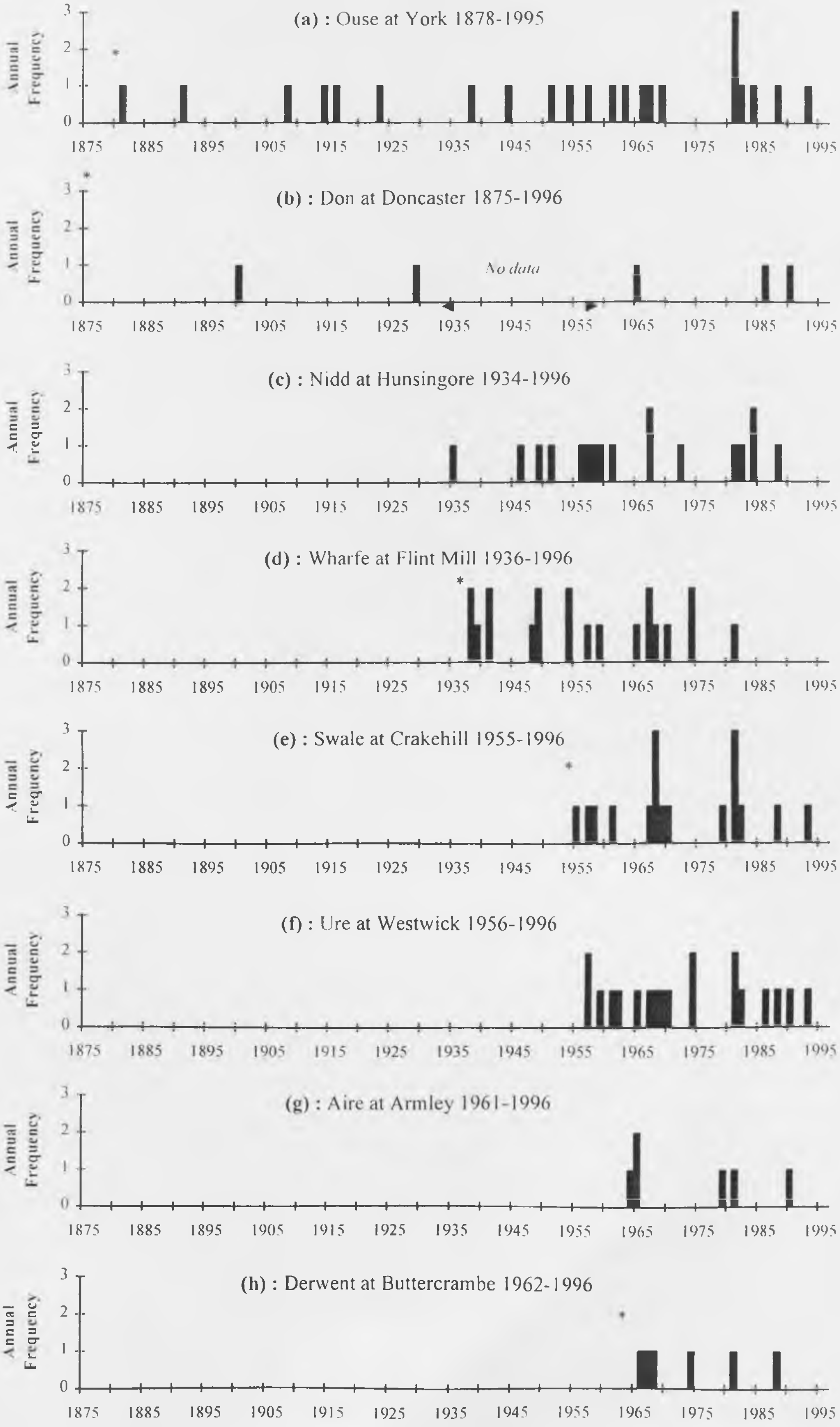
(e) : Swale at Crakehill 1955-1996

(f) : Ure at Westwick 1956-1996

(g) : Aire at Armley 1961-1996

(h) : Derwent at Buttercrambe 1962-1996

***Figure 5.17** : Annual frequency of floods generated by **cyclonic westerly** circulations*
** start of record*



(a) : Ouse at York 1878-1995

(b) : Don at Doncaster 1875-1996

(c) : Nidd at Hunsingore 1934-1996

(d) : Wharfe at Flint Mill 1936-1996

(e) : Swale at Crakehill 1955-1996

(f) : Ure at Westwick 1956-1996

(g) : Aire at Armley 1961-1996

(h) : Derwent at Buttercrambe 1962-1996

specific circulation types, and the general temporal variation within each of the four most common flood generating circulation types.

POT flood records for the Ouse at York and the Don at Doncaster extend to the late nineteenth century and show that this period was dominated by cyclonic flood generation particularly between the mid-1870s and mid-1880s (see figure 5.14). Westerly circulations generated less floods on the Don than the Ouse and south-westerly and cyclonic-westerly types accounted for relatively few events. Annual frequencies of cyclonic and westerly generated floods remained low until the 1940s. Higher frequencies of floods were generated by westerly circulations in the mid-1940s particularly on the Nidd and Wharfe. Since this time the number of westerly generated floods has decreased. Floods generated under cyclonic conditions also appear to have increased in the late-1940s and continued into the 1950s, unlike westerly circulations which were relatively low over this period. From this time onwards it is difficult to distinguish distinct periods when one or more circulation type dominated flood generation, emphasising the complex nature of flood generation and the fact that several circulation types can cause flooding in the same year. It does appear however, that between the late-1970s and mid-1980s, the incidence of cyclonic generated floods was increased at a number of sites. The frequency of cyclonic floods has declined since the mid-1980s, and westerly generated floods have increased particularly and the Swale and Ure.

A particularly clear trend is evident in the incidence of south-westerly generated floods (figure 5.16) which have shown a marked and sustained increase since the late-1960s. At York for example, in the 90-year period between 1878 and 1967 south-westerlies generated six flood events. Whereas in the 28-year period between 1968 and 1995 eight south-westerly generated floods have been recorded.

Floods generated under cyclonic-westerly circulations show variations between sites, with the Don, Derwent and Aire experiencing fewer cyclonic-westerly floods than the Ure, Swale, Nidd and Ouse, which show similarities in the timing of events.

In general it appears that the frequency of floods generated by cyclonic and westerly circulations are fairly evenly distributed over time and it is difficult to suggest any periods when one type clearly dominated. Both types are of primary importance in generating floods in the Ouse basin, although westerlies appear to be of far less importance of the Don and Derwent.

5.4.4. Variability of annual and seasonal frequencies of Lamb types, and links to flood frequency, magnitude and seasonality series

The dominant atmospheric circulation types which generated floods and the timing of their occurrence has been established in the previous sections. In an attempt to understand why certain circulations generate more floods in certain periods, this section investigates the annual and seasonal frequencies of the four Lamb types identified as being the most important in flood generation.

Clearly not every single day in the Lamb catalogue that is classified as being cyclonic, westerly, south-westerly or cyclonic-westerly will generate a flood event. This depends on the amount of precipitation delivered by each circulation type which varies markedly from day to day. Even so it would be expected that if the annual frequencies of these individual Lamb types increases or decreases, this would also increase or decrease the possibility that a flood would be generated by that particular type. This is not suggesting that if annual and seasonal frequencies of a particular Lamb type are low that no floods will be generated by that type, but simply that the likelihood of a flood being produced by that type would be reduced

Annual and seasonal frequencies of the four main flood generating types are presented since using annual frequencies alone may 'mask' seasonal changes which cancel each other out (Grew, 1996). However, prior to analysis of the Lamb catalogue, the seasonal relationships between circulations types and floods need to be established. In table 5.7 the number of floods generated by each circulation type has been calculated by combining all eight POT records and totalling the number of floods generated by each type. A seasonal percentage was then calculated for each circulation type so that the dominant season(s) could be identified when each type would be more likely to generate floods.

Table 5.7 : Percentage of floods generated in each season by each of the dominant flood generating circulations. Values have been calculated from all flood events at all eight POT sites.

	South-westerly (%)	Westerly (%)	Cyclonic (%)	Cyclonic-westerly (%)
Winter	58.46	73.37	44.82	67.26
Spring	9.23	15.67	18.33	7.96
Summer	0.00	0.00	9.96	1.77
Autumn	32.31	10.97	26.89	23.01

Table 5.8 : Mean annual frequencies of Lamb circulation types expressed as a percentage of the entire record 1861-1995. The four most common flood generating circulation types are highlighted.

Circulation Type	Mean %	Max %	Min %
Anticyclonic (A)	18.24	27.95	6.56
Anticyclonic-north-easterly (ANE)	1.35	4.37	0.00
Anticyclonic-easterly (AE)	2.41	5.48	0.27
Anticyclonic-south-easterly (ASE)	0.95	3.28	0.00
Anticyclonic-southerly (AS)	1.09	3.01	0.00
Anticyclonic-south-westerly (ASW)	0.88	3.29	0.00
Anticyclonic-westerly (AW)	4.60	11.48	1.64
Anticyclonic-north-westerly (ANW)	1.47	3.56	0.00
Anticyclonic-northerly (AN)	2.01	6.30	0.27
North-easterly (NE)	0.94	3.84	0.00
Easterly (E)	3.54	9.04	0.82
South-easterly (SE)	1.74	5.75	0.27
Southerly (S)	4.26	8.49	0.00
South-westerly (SW)	2.89	7.95	0.27
Westerly (W)	18.35	29.32	8.74
North-westerly (NW)	3.76	9.59	0.55
Northerly (N)	4.63	9.56	0.82
Cyclonic (C)	13.10	21.37	6.85
Cyclonic-north-easterly (CNE)	0.39	1.91	0.00
Cyclonic-easterly (CE)	1.10	3.56	0.00
Cyclonic-south-easterly (CSE)	0.46	1.92	0.00
Cyclonic-southerly (CS)	1.24	3.84	0.00
Cyclonic-south-westerly (CSW)	0.68	3.01	0.00
Cyclonic-westerly (CW)	3.87	9.59	0.82
Cyclonic-north-westerly (CNW)	0.88	2.47	0.00
Cyclonic-northerly (CN)	1.30	3.84	0.00
Unclassified (U)	3.89	7.67	1.37

Table 5.9 : Mean seasonal occurrence of Lamb circulation types per year expressed as a percentage of the entire Lamb catalogue 1861-1995 The four most common flood generating circulation types are highlighted.

Circulation Type	Winter %	Spring %	Summer %	Autumn %
Anticyclonic (A)	16.3	18.8	19.0	18.9
Anticyclonic-north-easterly (ANE)	0.8	1.8	1.4	1.3
Anticyclonic-easterly (AE)	1.9	3.5	2.3	1.9
Anticyclonic-south-easterly (ASE)	0.9	1.0	0.8	1.1
Anticyclonic-southerly (AS)	1.4	0.9	0.9	1.2
Anticyclonic-south-westerly (ASW)	1.1	0.7	0.8	0.9
Anticyclonic-westerly (AW)	4.6	3.7	5.6	4.6
Anticyclonic-north-westerly (ANW)	1.2	1.4	2.0	1.2
Anticyclonic-northerly (AN)	1.5	2.6	2.3	1.7
North-easterly (NE)	0.7	1.4	0.9	0.7
Easterly (E)	3.4	5.9	2.0	2.9
South-easterly (SE)	2.3	2.0	0.7	1.9
Southerly (S)	5.5	4.4	2.5	4.8
South-westerly (SW)	4.1	2.1	2.2	3.1
Westerly (W)	22.8	13.5	17.7	19.4
North-westerly (NW)	3.7	3.4	4.6	3.3
Northerly (N)	3.6	5.6	4.7	4.6
Cyclonic (C)	10.7	13.1	16.2	12.4
Cyclonic-north-easterly (CNE)	0.3	0.5	0.3	0.4
Cyclonic-easterly (CE)	1.0	1.4	0.9	1.1
Cyclonic-south-easterly (CSE)	0.5	0.7	0.2	0.5
Cyclonic-southerly (CS)	1.3	1.4	1.0	1.3
Cyclonic-south-westerly (CSW)	0.8	0.5	0.6	0.8
Cyclonic-westerly (CW)	4.1	2.8	4.4	4.1
Cyclonic-north-westerly (CNW)	0.8	1.0	1.1	0.7
Cyclonic-northerly (CN)	1.1	1.6	1.2	1.3
Unclassified (U)	3.7	4.2	3.8	3.9

The majority of floods generated by all four circulation types occur in winter, although the proportions can vary markedly. Westerly and cyclonic-westerly circulations show the highest winter percentages and cyclonic the lowest. Floods generated by cyclonic types are more evenly distributed throughout the seasons, with even the summer period accounting for 9.96% of all cyclonic flood events. South-westerly floods are generated primarily in winter, although the percentage of floods generated in autumn is also particularly high.

A second point which needs to be raised prior to analysis of annual and seasonal frequencies of individual circulation types concerns typical annual occurrences, which can significantly affect the range over which variation can take place. Grew (1996) suggests that it is variability in the most frequently occurring circulation types, which can have a large range of annual and seasonal values, that will have most influence on the flood record. Those circulation types with lower frequencies could not exhibit such a degree of variation, and therefore would not have as great an effect on the flood record.

Mean annual and mean seasonal occurrences of all Lamb types over the period 1861-1995 are shown in tables 5.8 and 5.9 . Westerly and cyclonic circulations are two of the most frequent types, occurring on average 18.35% and 13.10% of the time each year respectively. South-westerly and cyclonic-westerly only occurred on average 2.89% and 3.87% of the time each year between 1861 and 1995. This may suggest that explanations for variations in the flood record may be more evident in cyclonic and westerly annual and seasonal frequencies.

Variations in the annual and seasonal frequencies of Lamb circulation types have been the subject of a large number of studies (see chapter 2). One of the most marked and sustained trends has been the decline in westerly circulations since the 1950s (Jones & Kelly, 1982) which is evident in all seasons (Briffa *et al.*, 1990), and has continued into the late-1980s (Sweeney & O'Hare, 1992). Recent decades have seen a number of unusual variations, for example, the past two decades have seen an increase in anticyclonic and cyclonic synoptic systems, although variations are evident between seasons. Furthermore, Murray (1993) has shown that the 1980s have experienced the highest frequencies of southerly airflows over the entire Lamb catalogue. Sweeney and O'Hare (1992) have shown that there has been a twofold increase in the frequency of south-westerly days since 1960, and a sharp decline in north-westerly days during the 1980s.

The trends outlined above represent major changes in the Lamb catalogue over the past 135 years, although many more variations are evident on decadal scales. Figure 5.18 to 5.21 show annual and seasonal frequencies of the four circulations identified as being the dominant flood generators. The following section aims to establish associations between variations in flood frequency, magnitude and seasonality, and variations in the frequencies of the four main flood generating circulation types.

A peak in the number of floods generated under cyclonic conditions has been identified in the 1870s and early 1880s. This period coincides with an increased number of cyclonic days in all seasons (figure 5.18), although lower frequencies are evident over the autumn period High frequencies of cyclonic generated floods also occurred in the mid-1940s and 1950s, although this period does not appear to coincide with particularly high or low cyclonic frequencies in any season. In the mid-1980s a higher number of floods generated under cyclonic conditions does coincide with a marked rise in the frequency of cyclonic days. There are variations between seasons over this period, but since cyclonic floods tends to occur in all seasons the annual trend may be a good indicator of the overall influence of cyclonic days.

Associations between the number of westerly generated floods and annual and seasonal frequencies are also evident. Prior to the well documented decline in westerly circulations in the 1950s (figure 5.19), the number of westerly generated floods was high, particularly on the Nidd, Wharfe and Ouse. There is some evidence to suggest that the decrease in westerly circulations after the 1950s is reflected in the number of westerly generated floods, which appear to have declined on the Nidd and Wharfe in particular. The frequency of westerly circulations has increased in winter since the late-1980s, which is mirrored by an increase in westerly generated floods relative to the previous few decades on the Swale, Ure and to some extent on the Ouse.

The incidence of south-westerly generated floods has been shown to have increased since the 1960s, which coincides with the marked rise in annual and seasonal frequencies of south-westerlies (figure 5.19). The majority of south-westerly floods occurred after 1980, and as previously discussed, the 1980s has been identified as the most southerly decade in the entire record (Murray, 1993). Since the majority of south-westerly floods are generated in winter and autumn, the frequencies for these seasons have been examined to assess any links. Particularly high frequencies of winter south-westerly circulations in the mid-1970s does not coincide with a rise in the number of south-westerly generated floods. However, the increasing number of south-westerly generated floods in the 1980s is associated with a rise in frequencies, both in winter and autumn.

The relationship between cyclonic-westerly generated floods and annual and seasonal frequencies is less obvious (figure 5.21). A relatively large number of floods are being caused by cyclonic-westerly circulations despite the fact that annual and seasonal frequencies have been declining since the 1930s and remain very low.

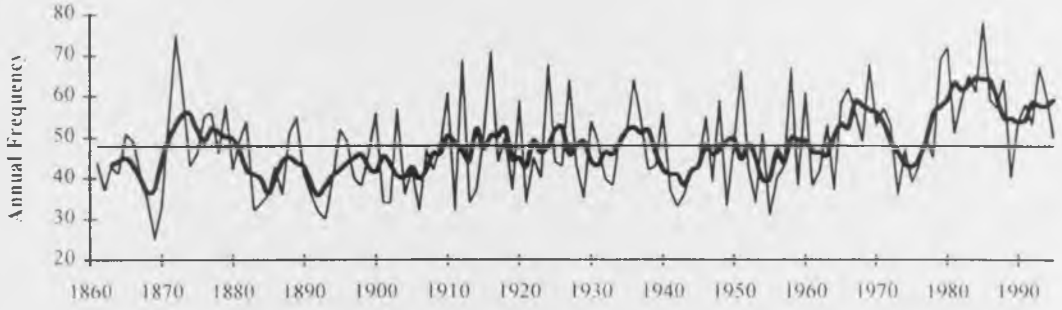
Assessing the relationships between variations in circulation type and flood magnitude is more difficult since the discharge of any flood event is dependent upon many factors such as, antecedent conditions and precipitation intensity, and not simply the weather type which inputs the precipitation which 'triggers' or generates the event. Some simple relationships between flood magnitude and circulation types have been established in section 5.4.5 although these are general relationships and not an attempt to explain temporal variations in flood magnitude. It would be unwise to suggest that observed changes in flood magnitude are simply due to a higher or lower incidence of a particular circulation type, however recent trends in flood magnitude do appear to track the pattern of cyclonic days. Peaks in the number of cyclonic days in the mid-1960s and between the late-1970s and early-1980s coincide with a period of high flood magnitude. Conversely, low cyclonic frequencies between the late-1960s and mid-1970s coincide with a period of particularly low flood magnitude.

In terms of flood seasonality one of the clearest variations in the flood record is the dramatic increase in spring POT events between the late-1970s and early-1980s. This may be due to the fact that the frequency of spring cyclonic circulations were high over this period. A second seasonal trend evident in the flood record is the decline in autumn floods since the 1960s. There appears to be no obvious explanation for this in terms of the autumn frequencies of circulation types, although a tentative link may be that this coincides with the rapid decline in both westerly and cyclonic-westerly circulations.

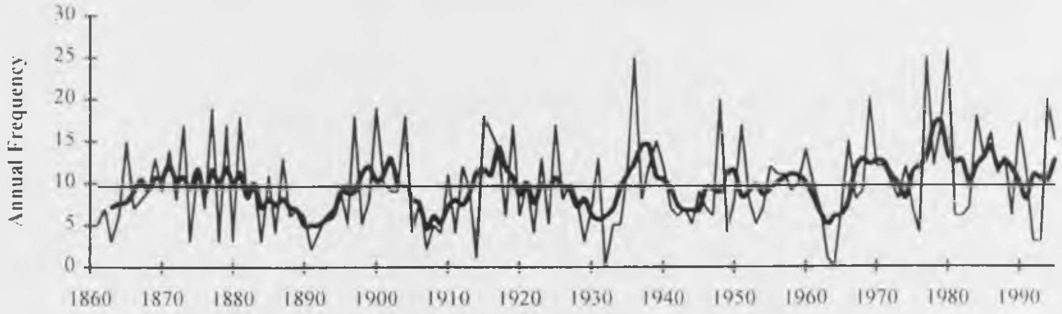
In summary, several strong links between annual and seasonal frequencies of the dominant flood generating circulation types and flood frequency have been established, particularly over the past thirty years or so. However, many variations in flood frequency cannot be explained by this simple association, and links with flood magnitude are even more difficult to assess. Future work could attempt to include more climatic parameters such as snow depth and temperature to investigate snowmelt floods, and to extend the period prior to the flood event that is considered in order to incorporate antecedent conditions into the study.

Figure 5.18 : *Annual and seasonal frequencies of* ***cyclonic*** *circulation type 1861-1995*

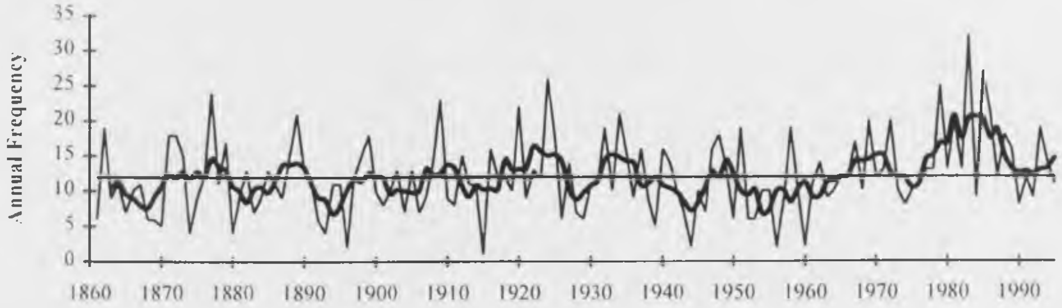
(a) : Annual



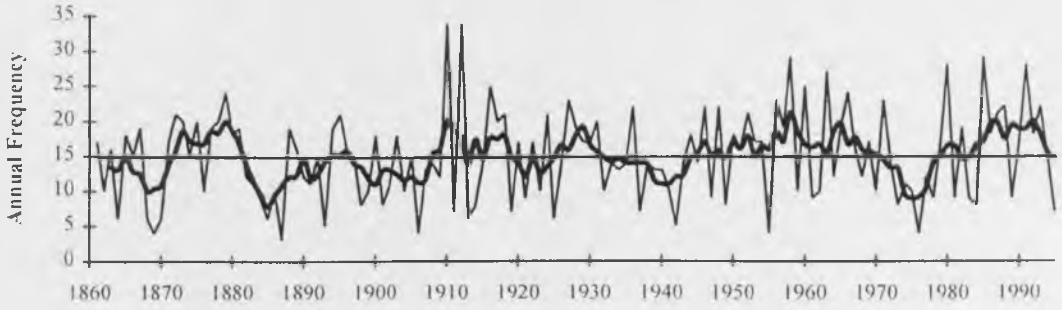
(b) : Winter (December-February)



(c) : Spring (March-May)



(d) : Summer (June-August)



(e) : Autumn (September-November)

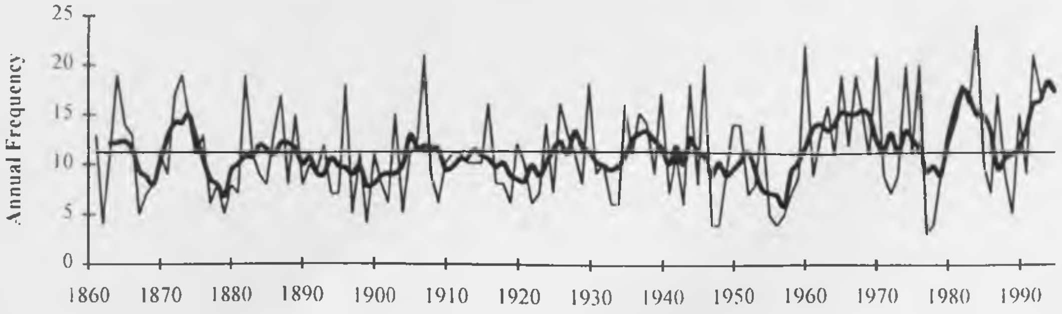
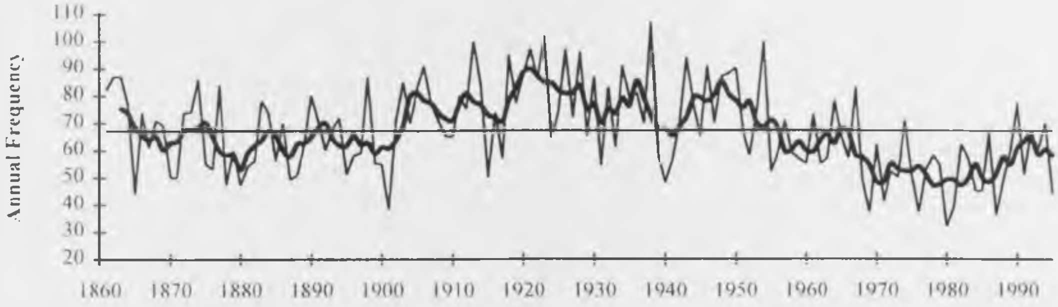
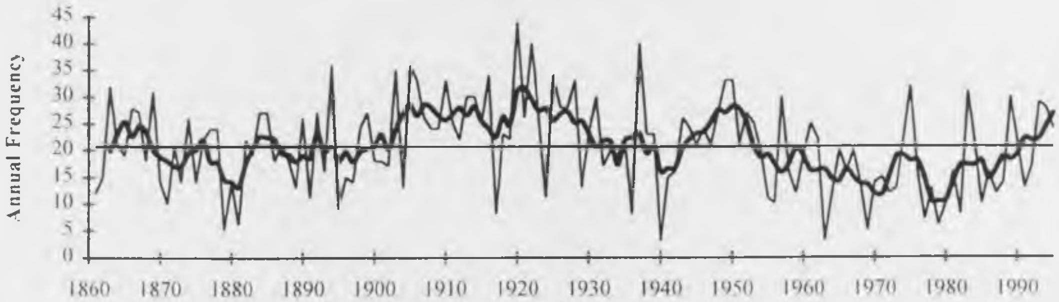


*Figure 5.19 : Annual and seasonal frequencies of **westerly** circulation type 1861-1995*

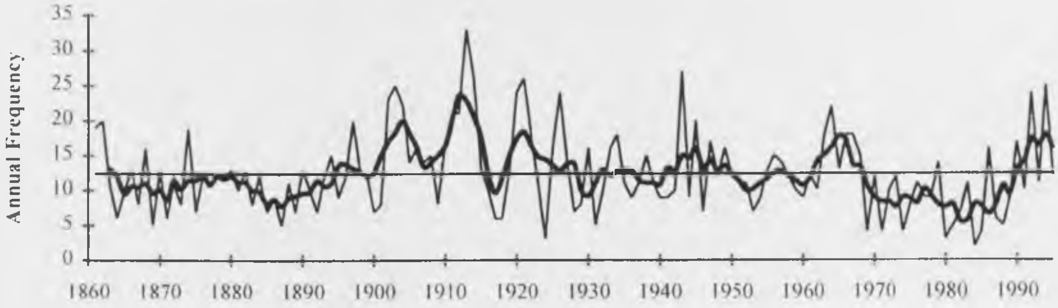
(a) : Annual



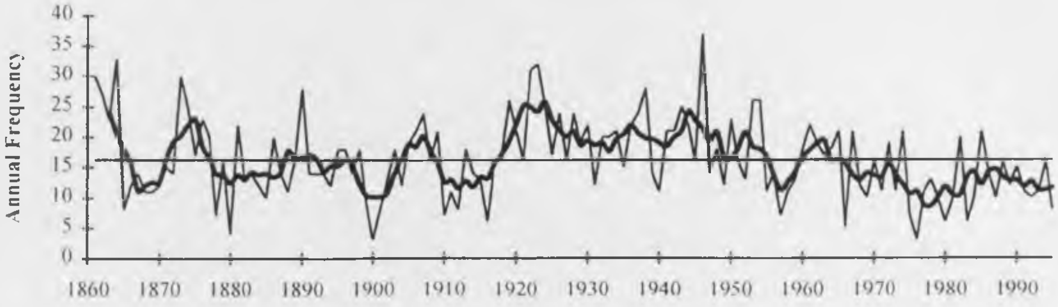
(b) : Winter (December-February)



(c) : Spring (March-May)



(d) : Summer (June-August)



(e) : Autumn (September-November)

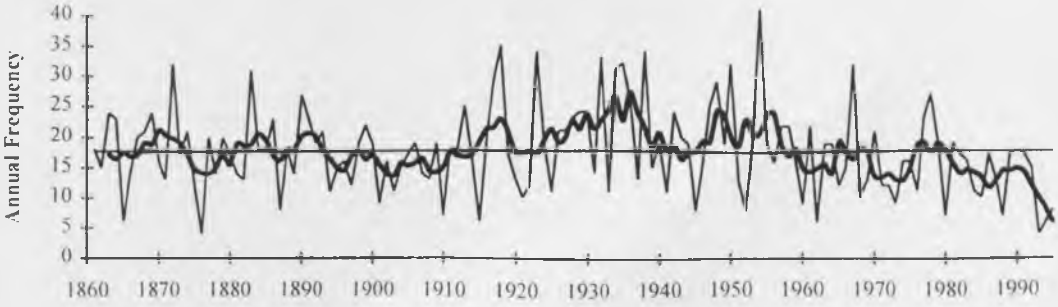
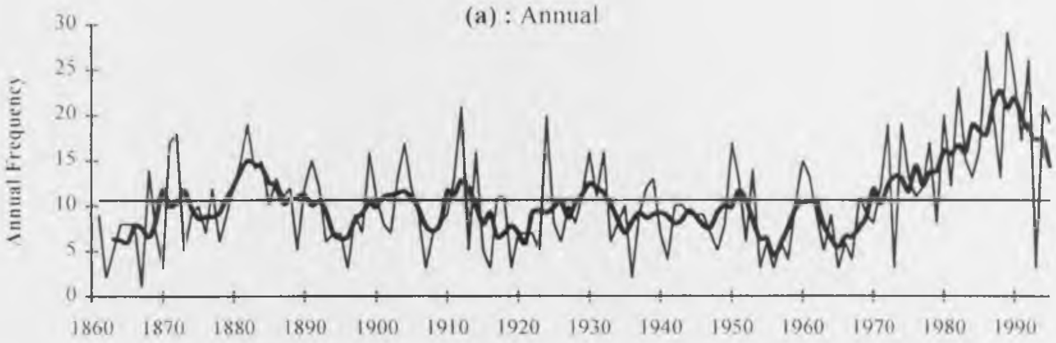
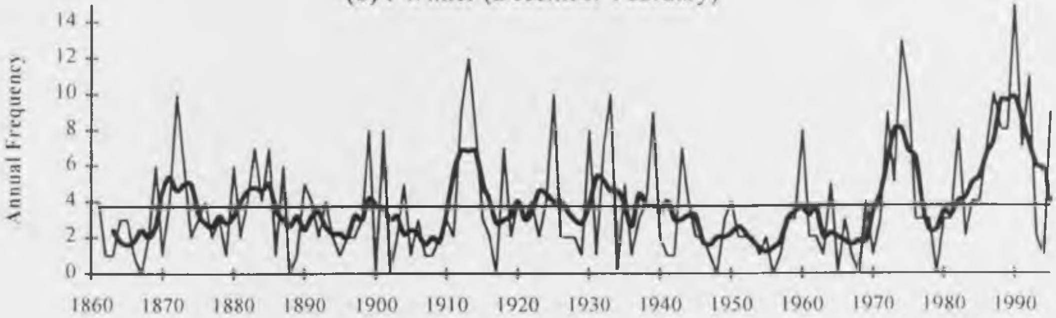


Figure 5.20 : Annual and seasonal frequencies of ***south-westerly*** *circulation type 1861-1995*

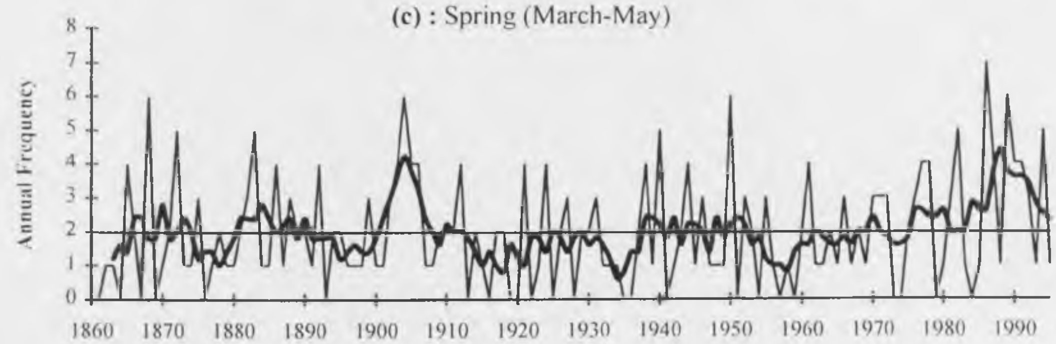
(a) : Annual



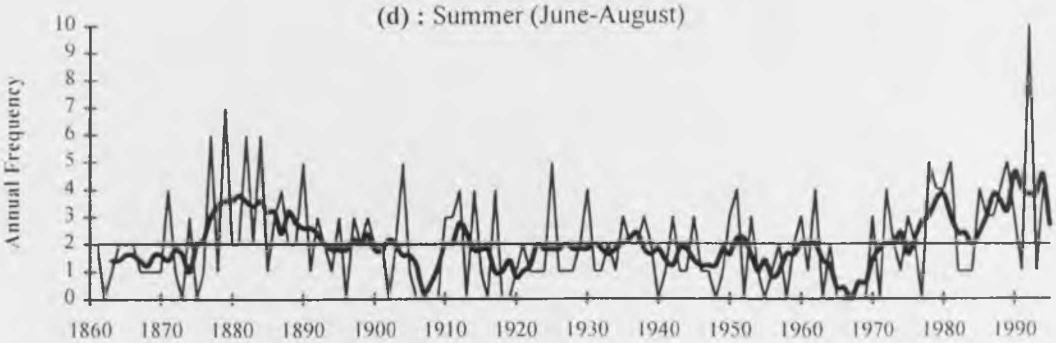
(b) : Winter (December-February)



(c) : Spring (March-May)



(d) : Summer (June-August)



(e) : Autumn (September-November)

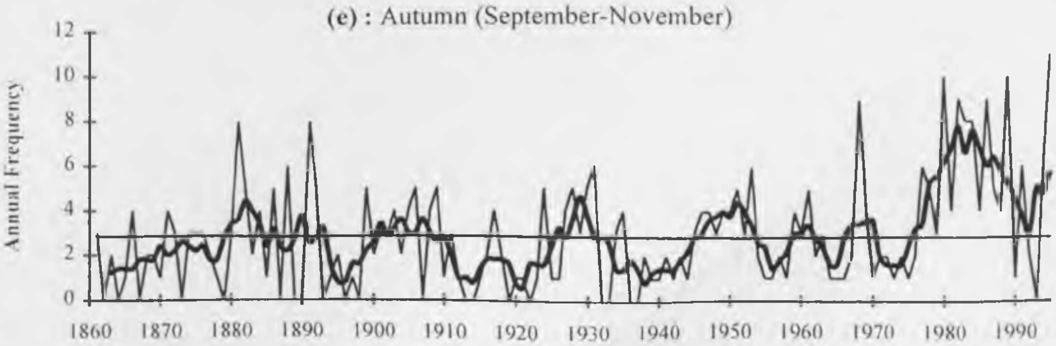
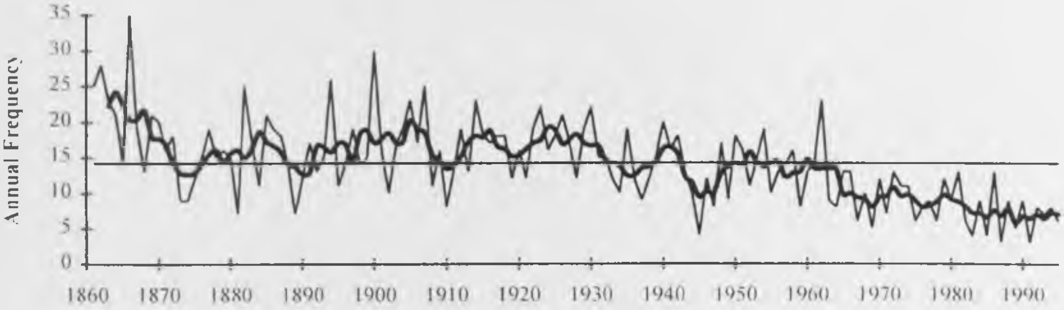
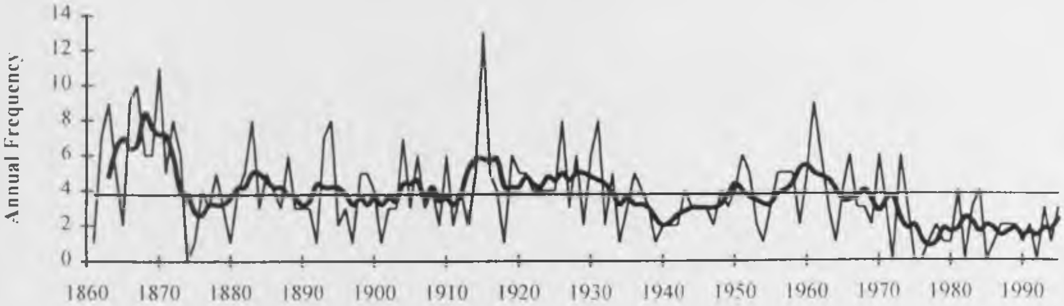


Figure 5.21 : Annual and seasonal frequencies of ***cyclonic-westerly*** *circulation type 1861-1995*

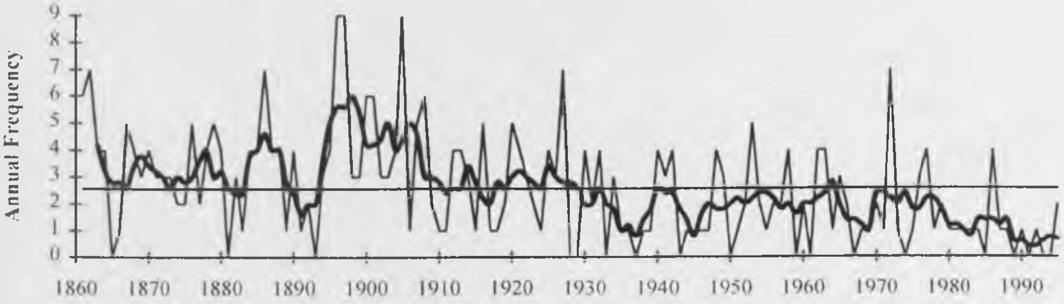
(a) : Annual



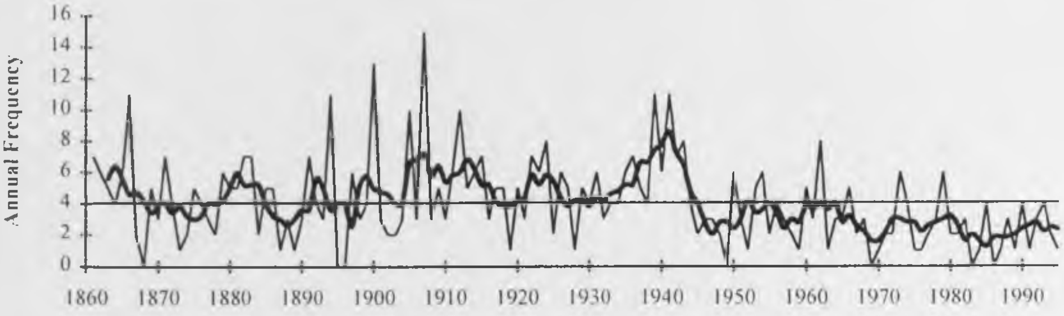
(b) : Winter (December-February)



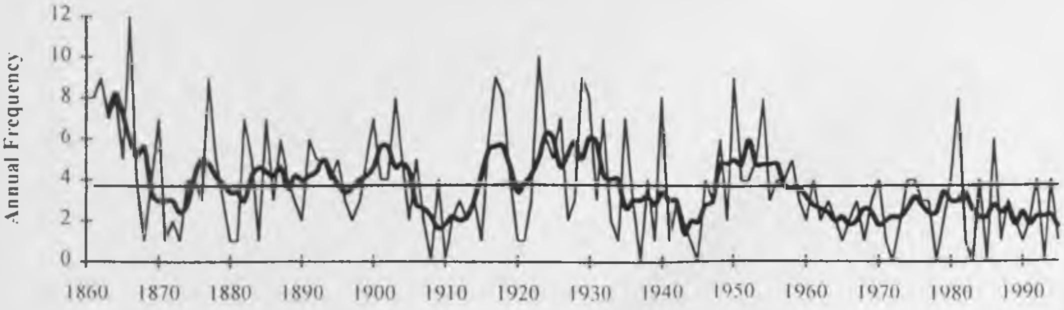
(c) : Spring (March-May)



(d) : Summer (June-August)



(e) : Autumn (September-November)



5.5. PROXY CLIMATE RECORDS : AD 1100 - 1900

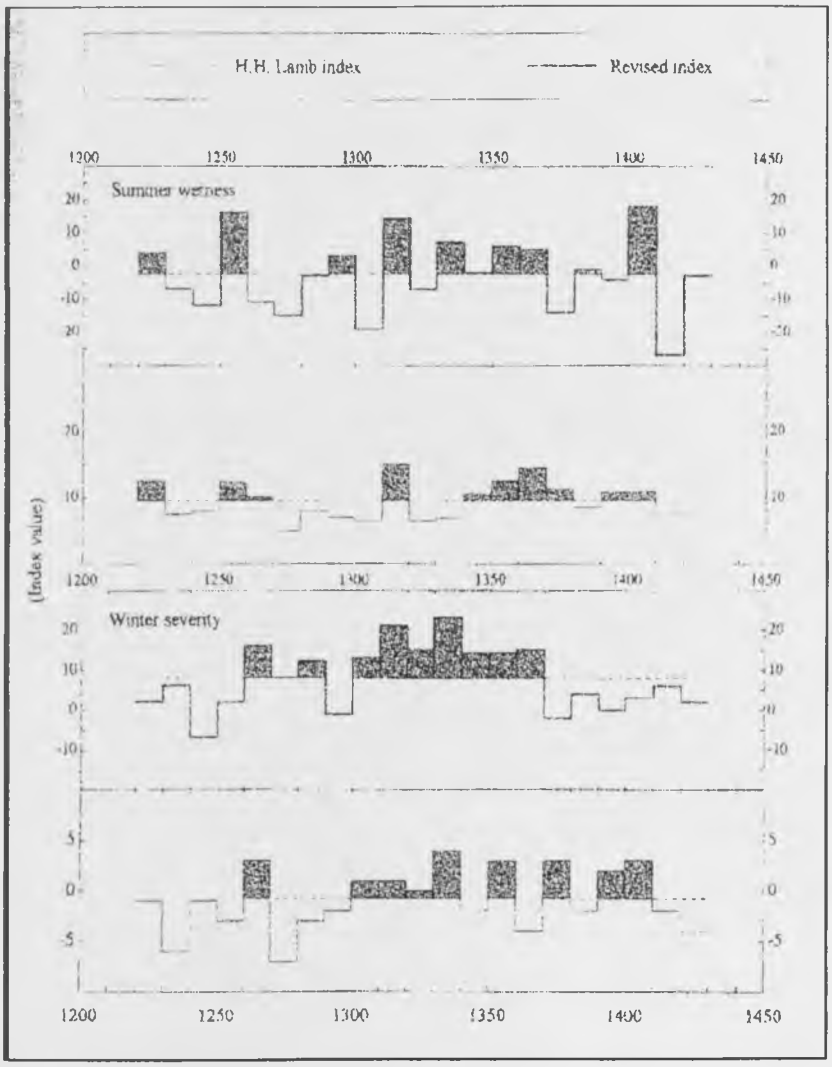
5.5.1. Introduction

Similar to flood records, prior to the advent of systematic recording of climate data, proxy sources must be employed to infer past climates. Sources of proxy climate data are comprehensively reviewed by Bradley and Jones (1995) and include tree ring data, pollen analyses, ice cores, marine sediment cores and the use of documentary evidence. Such data are often summarised for the British Isles as a whole or limited to an area where there are suitable sites for analysis, on peat-bogs for example. The aim of this section is to outline the climate history of the UK from around AD1100, which covers the period over which the majority of floods are documented in the Ouse basin. Records of temperature, precipitation and atmospheric circulation are considered. However due to the resolution of the data (usually annual or decadal) detailed analysis such as that carried out over the gauged period cannot be attempted. General links between climatic periods and the Ouse basin flood record are explored in the final section.

5.5.2. UK climate since the eleventh century

The period between AD 950 and 1300 has traditionally been called the 'Medieval Warm Period' which was thought to represent one of the warmest episodes since the beginning of the Holocene (Lamb, 1982). Although this may have been the case at certain times, more recent work has suggested that the climate of this period is far more complex (Ogilvie & Farmer, 1997). These authors have re-analysed documentary climate data between 1200 and 1440 from earlier work by Lamb (1977) and disregarded unreliable data through a detailed source analysis techniques. Ogilvie and Farmer (1997) have re-calculated Lamb's (1977) summer wetness and winter severity indices and these data are shown in figure 5.22. From the revised index this diagram shows that the decades between 1220 and 1250 were characterised by a low winter severity index, which increased between the decades 1260 and 1280. The 1290s showed a low winter severity index and were followed by a prolonged period of increased winter severity between 1300 and 1360. Between 1370 and 1420 there was a marked shift to a lower winter severity index. Although winter severity relates more to temperature than wetness, it may be the case that precipitation totals were also high during these periods, particularly in the form of snow. The summer wetness index shows greater decadal variation. However, since the majority of floods in the Ouse basin tend to occur in winter this index is not considered in detail.

***Figure 5.22** : Decadal indices of summer wetness (top) and winter severity (bottom) between AD 1220-1429, revised from Lamb (1977). Shaded decades are more severe (winter) or wetter (summer) than average (from Ogilvie and Farmer, 1997).*



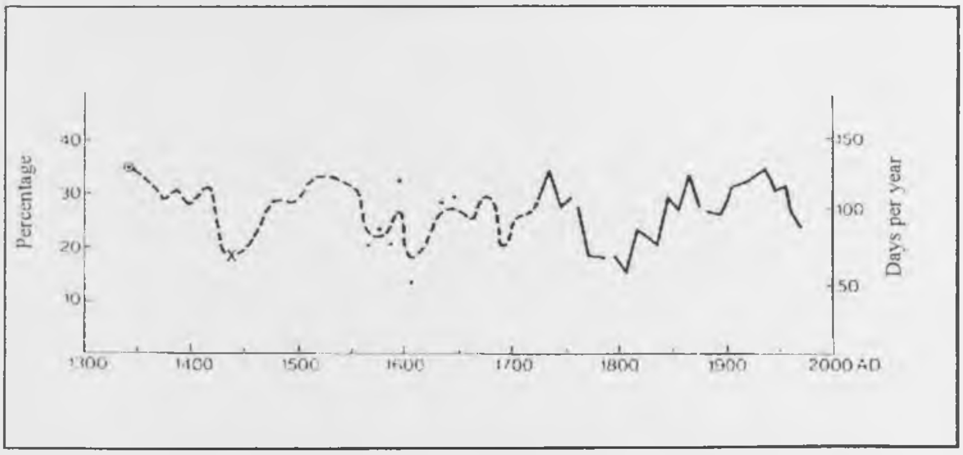
Other evidence suggests that there was an increase in wind storms and sea floods on low lying coasts of the North Sea in the thirteenth century. Lamb (1982) has attributed this to an increase in sea level due to glacier melting, and/or that there was a strengthened thermal gradient in latitudes between 50 and 65°N, due to arctic cooling which caused an increase in storm frequency and severity. After 1300, which is considered to represent the termination of the Medieval Warm Period, there was a period of cooling and a series of very wet summers and mostly wet springs and autumns (Lamb, 1982; Flohn & Fantechi, 1984).

Evidence from Bolton Fell Moss peat-bog near Carlisle suggests that the fourteenth and fifteenth centuries experienced particularly high surface wetness (Barber, 1981; Barber *et al.*, 1994). Over these two centuries there was an exceptionally high frequency of easterly winds which dominated over 50-55°N and 60-65°N both in summer and winter (Lamb, 1982).

Documentary reports of climate become more common in the sixteenth century, and it is generally accepted that there was a remarkably sharp change in the mid-sixteenth century from fairly warm conditions to the much cooler conditions experienced during the most recent Holocene neoglaciation, the 'Little Ice Age'. Recent studies have questioned traditional interpretations of climate during the Little Ice Age (e.g. Jones & Bradley, 1995). These authors suggest that this was a period characterised by a series of complex climatic anomalies, with marked seasonal contrasts and both warm and cold episodes. Rumsby and Macklin (1996) have summarised a number of recent climate studies encompassing the Little Ice Age and suggest that cooling began after the mid-sixteenth century and continued into the seventeenth century, there followed a warmer phase in the mid-eighteenth century and a second cooling phase in the late-eighteenth and early-nineteenth century. The nineteenth century has experienced a 'cool-warm-cool oscillation' (Rumsby and Macklin, 1996, p220) and the twentieth century has seen an amelioration in climate.

There are few long, reliable records of atmospheric circulation prior to the start of the Lamb catalogue in 1861. Each day between January 1781 and November 1786 has been classified according to Lamb's (1972) scheme based on maps derived by Kington (1975; 1980), however, this series is too short to be useful in this context. The only long-term data available are those compiled by Lamb (1967; 1972) which give the frequency of south-westerly surface winds derived from daily observations near London from 1699 and various diaries and monthly compilations to the fourteenth century (figure 5.23). South-westerly surface winds relate to westerly atmospheric circulations over the British Isles (Lamb, 1972; Kington, 1994), and can be used to make inferences as to the dominance of westerly types over certain periods. The frequency of south-westerly winds was high in the fourteenth century and low in the early-to-mid fifteenth century. High frequencies were again evident from the late-fifteenth century to mid sixteenth century, from which time there was a period of fluctuation until the mid-eighteenth century when there is a marked decline. Frequencies increased from around 1800 to a peak in the 1940s. Exactly how these fluctuations relate to documentary floods is difficult to establish, since these general trends are clearly not representative of the actual conditions that generated each flood event. These data and the general climatic characteristics presented over the last 900-years or so represent the best data available, therefore general links between climate and documentary floods will be attempted, taking into account limitations of the data.

***Figure 5.23** : Frequency of south-westerly surface winds over England since AD 1340, after Lamb (1972) and from Kington (1994).*



5.5.3. Links between documentary floods and climate records

General trends in climate over the last millennium have been outlined in the previous section. The aim of this section is to link periods with a distinctive flood regime to the prevailing climatic conditions and assess any possible relationships.

Several large floods were recorded on the Ouse, Aire and Calder between the decades 1260 and 1360. Notable precipitation extremes over this period include a run of extremely wet summers and mostly wet autumns and springs between 1313 and 1317, and the decade 1360 was particularly wet (Lamb, 1982). High values of Ogilvie and Farmer's (1997) revised winter severity index are evident throughout this period, apart from the 1290s (figure 5.22). Temperatures were generally declining from the Medieval Optimum (Lamb, 1982). Indeed the Bolton Fell Moss peat record (*cf.* Barber, 1981) show this to be a period of marked climatic transition with surface wetness changing from dry conditions to very wet. This period of flood activity also coincides with an increase in storminess with series of extremely severe sea floods occurring around North Sea coasts due to Arctic cooling and sea-level rise (Lamb, 1982). Lamb (1977) also suggests that rising sea level after 1300 caused tidal ranges to increase which would also cause the range of storm tides to increase.

Between the 1370s and 1550s no floods were recorded in the Ouse basin, the timing of which coincides with a marked decline in winter severity index around the 1360s which continues until the end of the record in the 1420s. In general, conditions were milder and drier than the previous period although temperatures were declining. However a short-lived warm phase was experienced in the early sixteenth century due to westerly winds over northern Europe and a high frequency of anticyclones affecting a zone of latitude 45-50°N (Lamb, 1982).

The period between 1550 and 1680 experienced the most severe flooding on record in the Ouse basin, events such as those in January 1564 and March 1614 on the Ouse at York having no modern or historical equal. Both these flood events and others in the basin were strongly influenced by snowmelt. The early part of this period is generally regarded to represent the onset of major cooling across Europe associated with the Little Ice Age, during which annual temperatures were greatly reduced and mountain glaciers advanced in Alpine (Grove, 1988) and Scandinavian regions (Karlén, 1988). The Little Ice Age was not simply a cold period, both warm and cool episodes occurred within it, with the most widespread cooling phase between the seventeenth and nineteenth centuries (Bradley & Jones, 1995). Marked variations in precipitation also occurred in the Little Ice Age. Lamb (1984b*)* suggests that extremely wet periods occurred when prevailing cyclonic storm tracks were shifted in a southerly direction due to the southward displacement of the Icelandic low, and also when stationary or slow-moving cyclonic circulations dominated, which would particularly effect those areas where south-westerly winds delivered precipitation.

Between 1681 and 1762 the flood record indicates that localised summer flooding increased in the Ouse basin, with no large spatially extensive lowland floods being recorded. The early eighteenth century is generally considered to represent a warmer phase of the Little Ice Age (Lamb, 1982), and the Central England Temperature (CET) record shows summer temperatures to be above average over this period (*cf.* Jones & Hulme, 1997). This increased incidence in summer flooding is probably a product of the more extreme seasonality that was experienced during the Little Ice Age, marked seasonal contrasts in both temperature and precipitation being common between the seventeenth and nineteenth centuries (Rumsby & Macklin, 1996).

Towards the end of the eighteenth century instrumental climate records are more common, and the homogenised England and Wales Precipitation (EWP) record commences in 1766 (*cf.* Gregory *et al.*, 1991; Wigley & Jones, 1987; Wigley *et al.*, 1984) and therefore allows for the detailed examination of precipitation patterns over the historic period. In terms of flood frequency, it appears that extensive lowland floods were again widespread on the Ouse towards the end of the eighteenth century, one example is the December 1763 event which was noted on both the Aire and Ouse (Environment Agency, 1995). Flood frequencies increased on the Ouse and Aire in the 1760s when the EWP record shows above average totals, particularly in autumn (*cf.* Jones *et al.*, 1997). 1768 was the second wettest year in the EWP record between 1766 and 1985 with 1247.3mm of precipitation (Wigley & Jones, 1987) and a notable flood was recorded in the Leeds and Bradford area in July 1768 when three bridges were destroyed (Piers, 1977).

Flood frequencies were reduced in the 1770s and 1780s, which coincides with low EWP totals particularly in winter and autumn. Three of the top ten driest years in the EWP record between 1766 and 1985 were recorded over this period, in 1780 (689.9mm), 1785 (719.4mm) and 1788 (614.0mm) (Wigley & Jones, 1987).

Between 1790 and around 1810 flood frequencies increased slightly, particularly on the Ouse and Aire, the EWP record show this to be a period of variable rainfall

The period 1760-1799 has been identified by Rumsby and Macklin (1994) as a time of increased frequency of large floods (>20 year return period) in the Tyne basin. They suggest that this is due to an enhanced meridional circulation regime (see chapter 3) due to cooler temperatures resulting in a larger equator to pole temperature gradient and a southward shift in climatic zones. Between 1800 and 1819 the circulation of the atmosphere was classified as intermediate, with no dominant circulation regime and reduced flood frequency and magnitude, and between 1820 and 1874 zonal airflows dominated resulting in an increased frequency of moderate (5-20 return period) flood events, due to warmer conditions that favour zonal flow which is characterised by a widely spaced, low amplitude configuration of the circumpolar vortex. These periods appear to relate well to the timing of flood events in the Ouse basin, with high flood frequency and magnitude in the late eighteenth century and again in the late nineteenth century which has also been classified as being more meridional in character (1875-1894). High flood frequencies are evident in the Ouse basin from the 1860s on the Wharfe and the 1880s on the Swale, combined with high frequencies and magnitudes in early gauged at the time records on the Ouse, Aire and Calder. In terms of precipitation between 1860 and 1900 three years appear in the top ten wettest on record in the EWP series 1766-1985, these are 1872 (1284.9mm), 1877 (1144.1mm) and 1882 (1146.2mm).

Gauged records are available on the Ouse basin from the late nineteenth century and links with climate have been discussed in a previous section.

5.6. FUTURE CLIMATIC CHANGES

In recent decades the climate of the British Isles has experienced some notable extremes, with well documented droughts in 1984, 1989-90 and 1995, and severe flooding in northern England in 1990, 1991 and 1995. Generally it appears that there has been a warming trend in the British Isles over the last two or three centuries and especially over the last two or three decades (Raper *et al.*, 1997). Evidence is increasing which suggests that these changes broadly mirror mean global trends, amid growing concern in recent years about the future implications of greenhouse gas emissions and global warming. Estimates of future climate change can be derived from simple global-average box models to complex three-dimensional models which couple ocean and atmospheric systems, the latter is required to assess detailed regional patterns of future climate changes (Raper *et al.*, 1997). In their recent paper Raper *et al.* (1997) summarise the results from HADCM 2, a complex model developed at the Hadley Centre which couples a twenty-level ocean model to a nineteen-level atmosphere model. Past and future estimates of aerosol and greenhouse gas forcing were based on IS92a, which is one of six possible emission scenarios defined by the Intergovernmental Panel on Climate Change (Leggett, 1992) for the twenty-first century. Raper *et al.* (1997) suggest this scenario 'adopts intermediate assumptions about future global population, economic growth, and the mix of conventional and renewable energy sources' (Raper *et al.*, 1997, p329.). Under this scenario the model predicts a rise in global temperatures of around 1.5°C by 2050 compared to the 1961-1990 average, and an increase of between 2.5°C and 3.0°C by the end of the next century.

However, Global Circulation Models (GCMs) used for these predictions are widely accepted as being subject to a number of limitations and uncertainties. One of the major problems is the coarse spatial resolution of GCM grids which results in poor regional estimates of future climate change (Mitchell *et al.*, 1990; Warrick & Barrow, 1991). Notwithstanding this problem the model suggests that for the British Isles there will be an increase in temperature of between 1.2°C and 1.6°C for winter and summer over the thirty year period centred on 2050, with a greater warming in the east than west. The model also predicts an increase in winter precipitation in Scotland of around 5%, and that the frequency of heavy rainfalls would increase over the British Isles, particularly in winter.

In general, climate change scenarios for the British Isles differ depending on the model and scenario applied, however there is a general consensus that precipitation will increase in winter (Arnell, 1992; Rowntree, 1990; Rowntree *et al.*, 1993; UKCCIPG, 1991) and that this increase will be greatest in the north and west (Arnell, 1992; Hulme & Jones, 1989; Santer *et al.*, 1990). Several authors have also suggested that a warming of the British Isles would result in a reduction in snow-cover (e.g Arnell, 1992; Raper *et al.*, 1997; Rowntree, 1990; Rowntree *et al.*, 1993) Similarly there would also be a reduction in frost occurrence. Rowntree *et al.* (1993) estimate that a 1°C rise in mean temperature would result in a 25% decrease in frost frequency How these changes would relate to flooding in the Ouse basin is subject to debate, particularly since Smith (1993) suggests that GCM predictions for precipitation changes tend to be less reliable than those calculated for temperature, and predictions of possible changes in extreme events is often poorly understood. However, authors in the USA (Knox, 1993), Australia (Smith, 1993), and Britain (Beven, 1993) all suggest that future climate change predictions would cause marked changes in flood frequency and magnitude.

In terms of the Ouse basin, the most probable effect of postulated increases in winter rainfall, storminess and flood producing rainfalls, would be to increase flood frequency and magnitude. However, reduced snow-cover may have a significant effect on flood magnitude, since most of the largest flood events in the basin are influenced by snowmelt. Therefore, extreme events caused by rapid snowmelt or rain-on-snow processes may become less frequent in a warmer world

Assessing the future effects of changes in the atmospheric circulation is more difficult with often conflicting views. Rumsby and Macklin (1994) suggest that an increase in global temperature would reduce the equator-pole temperature gradient, and lead to an enhanced zonal circulation regime which would in turn, increase the frequency of westerly circulation types. Westerly circulations are often associated with minor and moderate flood events in the Ouse basin and it could be expected that these events would increase in frequency if westerly circulations were to increase. Alternatively Sweeney and O'Hare suggest that a reduced thermal gradient would result in a continued decline in westerly circulations, which could cause an increase in large flood events due to increased convective activity and more intense depressions which has been postulated by Jones (1992).

Clearly there is a high degree of uncertainty as to the effects of predicted future climatic change of flooding in the Ouse basin, although given the unprecedented rate of change predicted for the twenty-first century, marked changes in flood regime can undoubtedly be expected.

5.7. SUMMARY OF THE CLIMATIC CONTROLS OF FLOODING IN THE OUSE BASIN

A number of large floods were recorded in the Ouse basin between 1260 and 1360; a time of marked climatic transition characterised by a cooling trend from the Medieval Optimum, increased winter severity, notable extremes of precipitation and an increase in storminess. There followed a flood free period of around 180-years when no floods were documented, and conditions were generally milder and drier with less severe winters. Some of the largest flood events in the Ouse basin were experienced around the time of the onset of the Little Ice Age, with particularly severe flooding between 1550 and the 1680s often with large snowmelt contributions. This period was also associated with a southward shift in the prevailing cyclonic storm tracks. During a warmer phase of the Little Ice Age localised summer flooding became more common, probably associated with elevated summer temperatures and an increase in high intensity, short duration convective storms. Flood frequency and magnitude increased markedly in lowland areas towards the end of the eighteenth and nineteenth centuries due to an increase in rainfall allied to an enhanced meridional atmospheric circulation regime.

After the late nineteenth century gauged records of floods and climate allow for a much more detailed analysis of relationships. Examination of annual, seasonal and POT rainfall series have shown that rainfall patterns often mirror changes in flood frequency and magnitude. For example, peaks in flood frequency and magnitude in the mid-1960s and between the late-1970s and mid-1980s were associated with increases in spring rainfall and the annual frequency of POT rainfall events. However, variations in rainfall series cannot explain many of the trends evident in flood records since, annual and seasonal records consider every single day over a specified period, and POT series, whilst examining the temporal variations of heavy rainfall do not necessarily relate to a specific flood event which depends on a variety of factors such as antecedent wetness, intensity and duration of rainfall and the depth of snow over the catchment. Many of these variables are difficult, or impossible to assess over the period covered by the gauged flood record. Records of daily atmospheric circulation date back to 1861, and since the character of the UK climate is controlled by these circulation types, an understanding of the synoptic generation of floods in the Ouse basin would lead to a better understanding of the mechanisms behind flood generation. To discern the direct controls of flooding we must study the period directly prior to each flood event, therefore a method was developed using POT flood records, daily rainfall records and the Lamb circulation catalogue to investigate the synoptic generation of flood events. It was found that four out of twenty-seven circulation types, cyclonic, westerly, cyclonic-westerly, and south-westerly generated 78.25% of all POT floods in the Ouse basin Cyclonic and westerly circulations were by far the most important types in terms of flood generation, although the relative importance differed between tributaries Catchments on the west of the Ouse basin with Pennine headwaters showed that similar proportions on floods were generated by similar circulation types, whereas the most easterly catchments showed significant differences. For example, on the Don and Derwent situated in the east of the catchment westerly and south-westerly circulations generated far fewer floods than anywhere else in the catchment, and the dominance of cyclonic circulations was greatly increased. The main reasons behind these patterns are that different circulations types deliver differing amounts of precipitation to different geographical areas. Cyclonic circulations do not exhibit the marked west-east rainfall contrast associated with westerly circulations and therefore cyclonic generated floods become more common on the eastern side of the catchment. Cyclonic circulation types also appear to generate the majority of the highest magnitude events, whereas westerly circulations more commonly generate floods of a more minor or moderate magnitude. Temporal variations in flood frequency appear to be linked to variations in the annual and seasonal frequencies of the important flood generating circulation types. A high proportion of westerly generated floods in the mid-1940s was associated with a peak in westerly frequencies in all seasons, the well documented decline in westerly frequencies since the 1950s appears to have resulted in a reduced frequency of floods generated by this type. Furthermore, an increase in flood frequency in the late-1970s to mid-1980s was allied with a rise in the frequency of cyclonic frequencies and cyclonic generated floods. One of the most dramatic increases, however, has been shown in the annual and seasonal frequencies of south-westerly circulation types. The marked increase from the 1960s has resulted in a rise in the number of south-westerly generated floods.

Predictions of future climate change suggest an increase in winter precipitation, the frequency of flood producing rainfalls and storminess, all of which could combine to increase both flood frequency and magnitude. At the hemispheric scale, a warmer world would result in a reduced equator-pole temperature gradient which some authors suggest would result in an enhanced zonal circulation and an increase in westerly circulations over the UK. If this were to be the case, then given associations derived in this chapter, this may suggest that the frequency of minor and moderate magnitude floods may increase. Allied to this a warmer world would result in less snowcover which may cause a reduction in flood magnitude. Other authors suggest that a decreased thermal gradient would further reduce the frequency of westerly circulations, and this may favour the generation of larger floods under cyclonic conditions due to an increase in convective activity and more intense depressions in the Ouse basin.

CHAPTER 6

LAND-USE CHANGE IN THE YORKSHIRE OUSE BASIN

6.1. INTRODUCTION

This chapter attempts to evaluate major land-use changes which have occurred in the Yorkshire Ouse basin over the past 150 years or so. The majority of records pertaining to land-use are relatively short, therefore longer term variations are less detailed and often derived from national assessments. Recently, it has been suggested that changes in land-use have resulted in increased flooding in several areas of the basin, particularly areas subject to land drainage (see Caufield, 1982; Oldfield, 1982). It has also been suggested that there may be a link between greatly increased sheep numbers and increased flooding in the Yorkshire Dales (Sansom, 1996) In this case over-grazing leads to a reduced in the vegetation cover and higher rates of runoff.

Four main aspects of land-use change are investigated in this chapter, these are the temporal and spatial variation in (1) agricultural land-use (2) agricultural land drainage (3) channelization in the basin and (4) reservoir construction. The final section attempts to summarise major land-use changes and comment on their effects on flood regime, and suggests links to the flood record. (Urbanisation is not considered in detail here, since the majority of towns and cities in Yorkshire were well established prior to gauged flood records, and it would be extremely difficult to assess the urban impact on flood hydrology over such a long period.)

6.2. AGRICULTURAL LAND-USE CHANGE IN THE YORKSHIRE OUSE BASIN

One of the most detailed datasets in the UK relating to land-use change is that derived from annual agricultural returns, which have been published since 1866. These records cover the entire period of systematic flood recording in the Ouse basin and comparisons can be made between large-scale changes in agricultural practices and variations within the flood record. This section reviews general agricultural trends in the UK from the mid-nineteenth century, and examines county statistics for the Ouse basin to assess regional agricultural change.

6.2.1. History of British agriculture since the nineteenth century

The main trends in nineteenth and early twentieth century agricultural land-use in Britain have been reviewed by Sheail (1973) and Cherry and Sheail (in press), and post-war trends by Parry (1991). These reviews form the basis of this summary which outlines the main temporal and spatial variations in agricultural land-use change in Britain as a backdrop to those described for the Ouse basin in the next section.

The period between the mid-nineteenth century until the mid-1870s is regarded as the prosperous 'high farming era'. Cherry and Sheail (in press) have estimated that 80% of the population were fed from home-grown produce during this period, which was facilitated by an expansion in underdrainage, the enlargement of fields, straightening of boundaries, and a number of technological innovations such as the invention of the steam plough and advances in fertilisers and breeding practices. This period of prosperity was followed by a severe depression in the last quarter of the nineteenth century, which was particularly pronounced over the two periods between 1875-84 and 1891-99. This decline in UK agriculture was largely attributed to increasing overseas competition, with imports of wheat increasing two-fold between 1850 and 1872. The main consequence of this in terms of land cover was the reversion of arable land to grassland, and Cherry and Sheail (in press) suggests that the area of land growing corn crops in Britain fell by 16% between 1868 and 1891. Between the end of the nineteenth century and the outbreak of World War One the agricultural economy recovered, although still remaining relatively unprofitable. Over the period 1871 to 1891 the gross output of English agriculture had fallen by 13%, however, by 1911 this had recovered to the 1871 level.

The use and management of farmland in England and Wales has been studied in detail by Sheail (1973) between 1915 and 1919, who suggests that both the government and public became aware of the need for increased home production. The objectives of British farming changed and the government intervened in the management and use of individual farms and fields for the first time, particularly encouraging the ploughing up of grassland areas for crop production.

After the First World War widespread economic depression set in which resulted in the reversion of arable to grassland for livestock production in the 1920s and 1930s (Bowler, 1991). Demand was reduced for agricultural products and Parry (1991) estimated that arable land area declined by around 8% between 1931 and 1938. After 1938 there was an increase in ploughing grants and compulsory powers were given to the County War Agricultural Executive Committees, which reversed the trend of declining arable area (Parry, 1991). Increased home production was required in the war period due to shipping blockade (Bowler, 1991), and the arable area increased by 8% between 1940 and 1943, and by 4% in 1944 (Parry, 1991). This increase in arable land has been sustained upto the present day throughout the UK due to technological developments and the increased mechanisation of arable farming.

Parry (1991) suggests there are four main components of post-war land-use change in Britain, the growth of urban areas, changes in the agricultural sector, the extension of forest and woodland and the growth in competition for rural land from what he terms 'quasi-urban' uses such as for recreation and water gathering. However, even though good quality agricultural land has been lost to urban development, and some upland areas to afforestation, Parry suggests that overall agricultural production has substantially increased since 1945. Changes in farm practices since this period which have increased production include the intensification of farming, increasing specialisation and the increasing scale of operations. In terms of upland areas, Parry (1991) estimates that between 1933 and 1980, 15% of UK rough land (unimproved land) has been transferred to improved farmland.

6.2.2. Agricultural land-use change in the Yorkshire Ouse basin since 1866

The first systematic annual return of crops and land-use was carried out in England and Wales in 1866 by the Board of Agriculture. Since this time, annual returns have been compiled for every agricultural holding on the 4th July each year. The early returns were completed on a voluntary basis by individual farmers until 1925, when it became law that holdings of more than one acre must make an annual return (Hooke & Kain, 1982).

A number of problems concerning the accuracy and reliability of the annual agricultural census have been discussed in detail by Clark *et al.* (1983). These authors point out that the major problem for historical studies are the changes in information collection and presentation, which can reduce the comparability of data over time. This problem is difficult to address since the majority of early original records have been destroyed (Hooke & Kain, 1982). Further complications include, errors by individual farmers and their lack of co-operation, particularly in the early period. Location of farm boundaries also cause problems since particular holdings may not lie wholly within one parish. Not withstanding these criticisms, Clark *et al.* (1983) stress that problems of inaccuracy are more common within individual parishes, rather than at the county or national level and that, on the whole, 'the census is quite remarkably reliable by international standards' (Clark *et al.*, 1983, p119).

Parish data for England and Wales are available at the Public Records Office at Kew. However, due to the large study area and time constraints of the project, parish data were considered too detailed and county statistics were used, as these data are more readily accessible.

Annual agricultural returns from 1866 to 1939 are contained in a statistical appendix in the *County Report to the First Land Utilisation Survey of Great Britain*, and are available for the North (Wooldridge, 1945) and West Riding (Beaver, 1941) of Yorkshire, which covers the majority of the study area. These series were updated from 1939 to 1995 using the annual publication of *Agricultural Statistics, United Kingdom*, between 1939 and 1990, and *The Digest of Agricultural Census Statistics, United Kingdom*, from 1991 onwards.

Complications occurred within the data set due to large-scale county boundary reorganisation in 1974, when the North Riding became North Yorkshire and the West Riding, West Yorkshire. Therefore, the data have been treated as separate series either side of this breakpoint. Two main land classifications were used between 1866 and 1980, total area of arable crops and total area of permanent grassland, which represent the majority of land cover in this area. Since 1980 data presented in the reports have been much more detailed, documenting the area of a large number of individual crops. Due to these problems data from 1974 onwards have been amalgamated into arable and permanent grassland categories, and arbitrary units used as a measure of land area.

Annual area of arable crops, permanent grassland and rough grazing are shown in figure 6.1 for the North Riding of Yorkshire and in figure 6.2 for the West Riding of Yorkshire. The trends displayed in these diagrams exhibit distinct similarities with the national trends outlined in the previous section. The area of permanent grassland steadily increases, and arable area decreases from the start of the record until the end of the nineteenth century in the West Riding and the start of the First World War in the North Riding. This represents a period of agricultural depression which was particularly pronounced in the last quarter of the nineteenth century. Between 1866 and 1914 the total arable area declined by 6.6% in the North Riding and by 7.8% in the West Riding, over the same period permanent grassland increased in area by 13.8% in the North Riding and 12% in the West Riding. The increased need for home food production in the First World War resulted in a 3% increase in arable area in the North Riding Between 1914 and 1918. After this time a period of economic depression caused large areas of arable land to be reverted back to grassland. Arable area fell by 6.1% in the North Riding and West Riding between 1918 and 1939. However, the most dramatic shift in agricultural land-use occurred around the onset of the Second World War. Increasing government grants and a sustained plough-up campaign caused a 12.3% increase in arable area in the North Riding and a 11.1% increase in the West Riding. This was associated with a marked decline in the area of permanent grassland which fell by 14.7% in the North Riding and 13.8% in the West Riding of Yorkshire.

Post-war trends in the Yorkshire counties show that arable area declined slightly after the Second World War, and the area of permanent grassland increased. Arable area has steadily increased in the North Riding since the mid-1950s, and area of permanent grassland has declined. A different trend is evident in the West Riding, a period of stability after the Second World War has been followed by a relative decline in the area of both arable and permanent grassland.

The area of rough grazing has increased steadily in both counties since the beginning of the record, associated with a rise in the numbers of livestock, although this increase has been more pronounced in the North Riding.

6.3. AGRICULTURAL LAND DRAINAGE IN THE YORKSHIRE OUSE BASIN

In response to extreme flooding in the Yorkshire Ouse basin in January 1982, Caufield (1982) reported the view expressed locally that recent upland and lowland agricultural drainage schemes may have exacerbated downstream flooding. Robinson (1990) suggests that the role of upstream drainage is often questioned when large floods occur, citing examples of studies in Scotland (Learmonth, 1950) and Wales (Howe *et al.*, 1967) after a series of large flood events in the 1940s.

To assess the effects of agricultural land drainage schemes, data are required on the timing, extent, location and type of drainage within a catchment. Field drainage data were collected by MAFF in England and Wales between 1971 and 1980, in an attempt to improve drainage system design (Robinson, 1990). Data over this period pertaining to the Ouse basin were requested from MAFF. Unfortunately however, this information could not be located. Therefore, the main source of data relating to lowland underdrainage is found in country-wide reviews, such as Phillips (1989), for the nineteenth century, and Robinson (1990) for the twentieth century. Data relating to hill drainage is often more scarce, however, Robinson (1990) studied the timing and extent of moorland gripping in the Yorkshire Dales. The work was carried out during a 'window of opportunity', when MAFF began to ease its normal confidentiality constraints as to where grant-aid for drainage schemes was given (Robinson, per comm.). Since this study, many of the original files have been destroyed under new MAFF policy (Robinson, 1990), and were not available for consultation. Chapter three reviewed various upland and lowland drainage techniques and their possible effects on flood regime. This section attempts to investigate the temporal and spatial patterns of agricultural land drainage.

Figure 6.1 : Annual area of arable crops, total permanent grassland and rough grazing in the North Riding 1866-1995

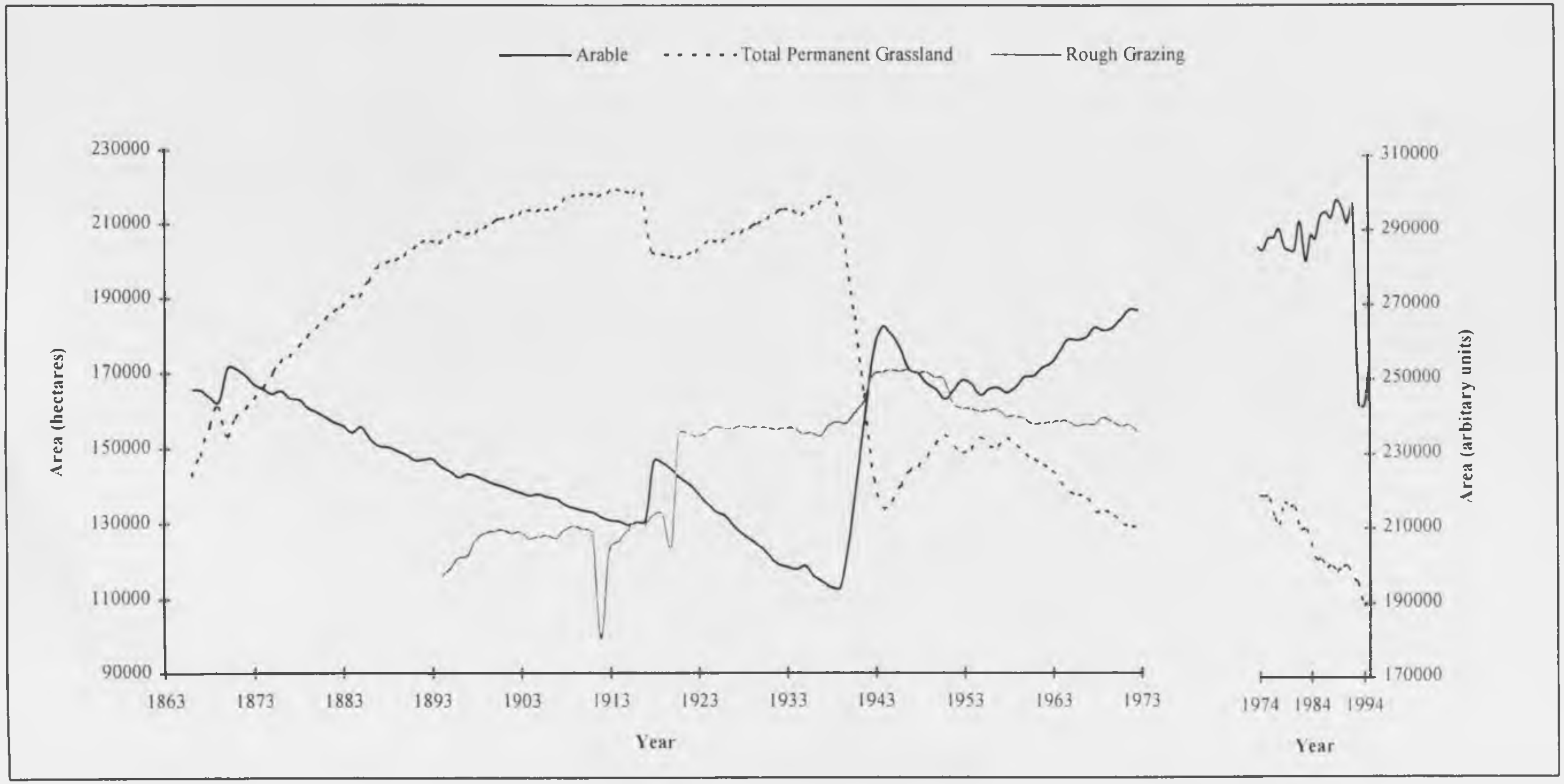
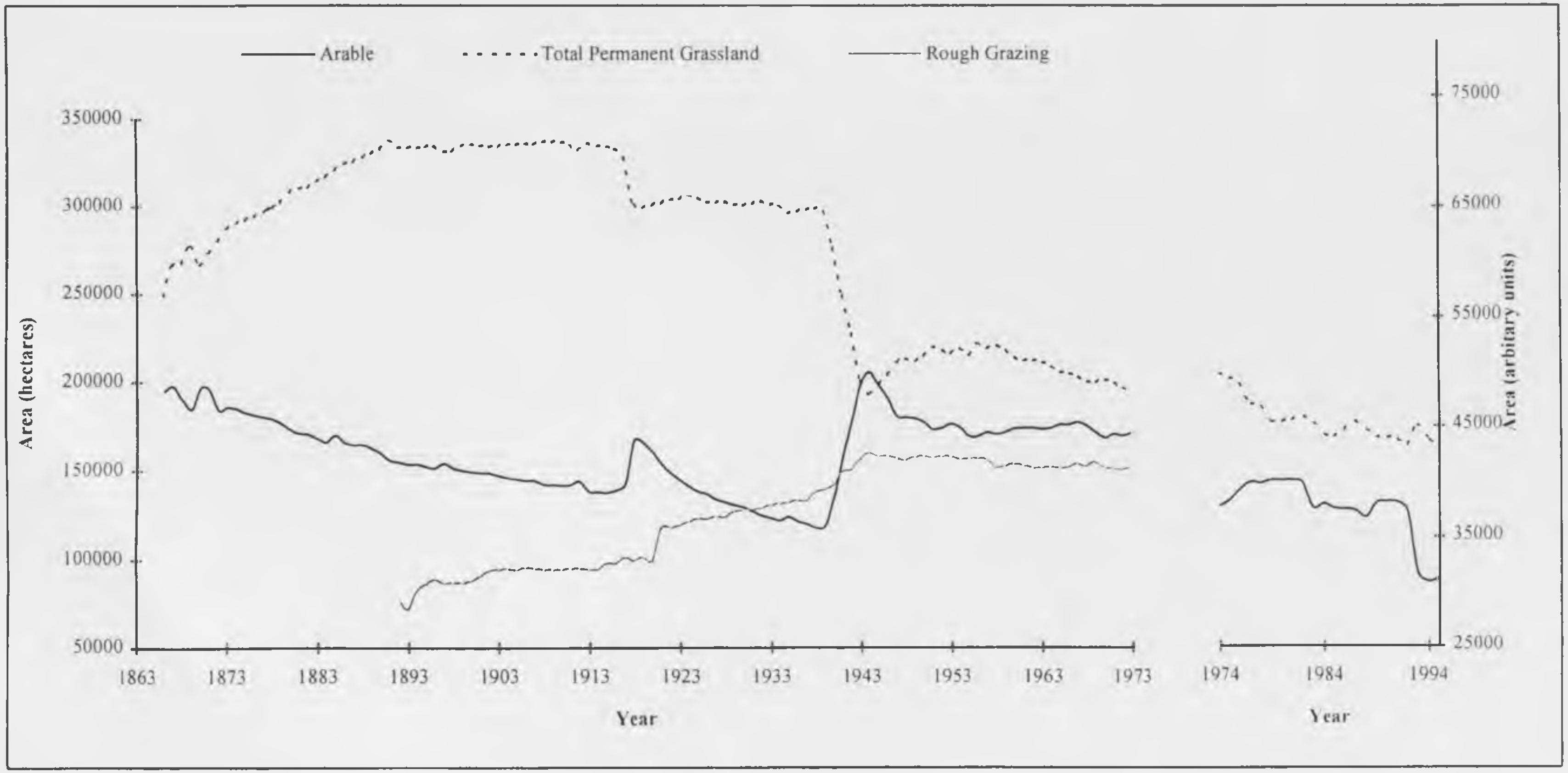


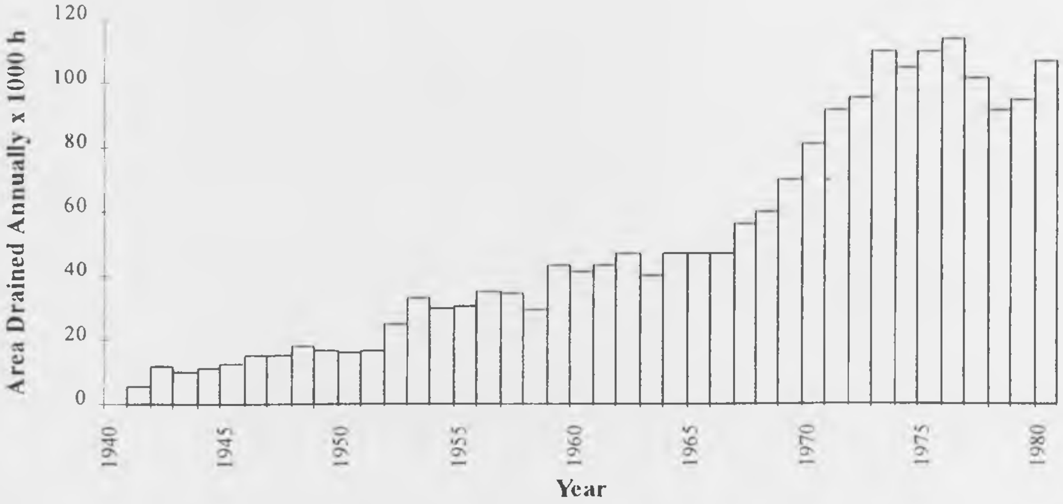
Figure 6.2 : Annual area of arable crops, total permanent grassland and rough grazing in the West Riding 1866-1995



6.3.1. History of agricultural land drainage in Britain

The need for agricultural improvement in Britain was realised soon after the enclosure of common lands at the beginning of the seventeenth century (Robinson, 1990). However a lack of suitable materials and reliable drainage systems resulted in little drainage activity. Tile drains became available in the 1820s and resulted in the introduction of underdrainage in many areas. Although it was not until the late 1830s when suitable materials and reliable drainage systems were available, that large-scale land drainage was attempted (Phillips, 1989). Tile making machines were invented in the 1830s and a reliable system of drainage had been developed by James Smith, who advocated the use of closely spaced shallow parallel drains. Drainage activity increased further in the 1840s due to the introduction of government drainage loans, new drain-pipe making machines, and an improved drainage system developed by Josiah Parkes who suggested the use of deep parallel drains (Phillips, 1989). The most intensive period of underdrainage in the nineteenth century occurred over the thirty year period between 1840 and 1869 (Phillips, 1989), which coincided with the 'high farming era' of agricultural prosperity (Robinson, 1990). There followed a prolonged period of agricultural depression towards the end of the nineteenth century which resulted in a marked reduction in the number of drainage schemes between the 1880s and 1930s (Nicholson, 1943; Trafford, 1970). In 1939 government grant-aid was introduced in England and Wales towards the cost of underdrainage, hill drainage and arterial channel drainage (Robinson, 1990). The onset of the Second World War resulted in the need for increased agricultural production, which required pasture improvement for arable crops. Figure 6.3 shows the annual area of grant-aided field drainage in England and Wales between 1940 and 1980. The area drained annually has increased from 1939 and reached a peak of around 100 000 hectares per year in the 1970s (Stansfield, 1987; Robinson, 1990). Drainage statistics are not available after 1980, although Stansfield (1987) has estimated that around 50 000 hectares of existing drainage deteriorates and become ineffective each year, and suggests that the area drained in the late 1980s was less that this figure.

***Figure** 6.3 : Area drained annually by Grant Aided field drainage in England and Wales 1940-1980. (redrawn from Stansfield, 1987).*



6.3.2. Temporal and spatial patterns of agricultural land drainage in the Yorkshire Ouse basin

It has been shown at the catchment scale that the impact of land drainage on peak flows depends upon a number of site-specific factors (Robinson, 1990). One of the key elements when trying to assess the effects of land drainage is the location of drainage schemes within the catchment (Newson & Robinson, 1983; Robinson, 1990) as this can effect the timing of flood peaks from different parts of the catchment. For example, drainage schemes in the lower reaches of a catchment which speed runoff into the main channel may reduce the flood peak downstream since this may not combine with peak flow from the uplands. Similarly, lowland drainage schemes which slow runoff into the arterial channel may increase the peak flow. These effects may be the opposite when considering upland drainage schemes (Newson & Robinson, 1983). Other catchment factors such as variations in soils and slope may also cause a different response to drainage, as will the type of drainage scheme implemented, particularly when considering the spacing and density of drains, and whether or not secondary treatment has been carried out. All of these factors combine to make extrapolation from the results of plot and catchment studies to other areas very difficult (Robinson, 1990). This study simply attempts to relate the timing of widespread drainage schemes to the flood record and assess the possible links. However, this is again limited by the availability of data, which are particularly poor prior to the 1940s. Because regional drainage data for the Ouse basin are not generally available, the majority of data considered comes from country-wide reviews of land drainage, some of which gives detailed information on the geographical distribution of both underdrainage and hill drainage.

The work of Phillips (1972) probably represents the only detailed study into land drainage in the Yorkshire area during the nineteenth century. The timing and extent of underdrainage expenditure are considered for the Yorkshire estate of the Earl of Scarborough The estate was in the West Riding of Yorkshire between Doncaster and Rotherham, and covered an area of 6041 acres in 1896. Although this is a very small area when compared to the Ouse basin, such a study can give an indication of the general trends of lowland underdrainage in the area. Phillips suggests that the timing and nature of underdrainage on the estate are broadly comparable to those suggested for England and Wales as a whole.

Widespread underdrainage began on the estate around 1840 associated with the availability of cheap materials and reliable drainage schemes. The period of most intense drainage activity and expenditure occurred between 1861 and 1883. The decline in drainage activity after 1883 was attributed to a declining agricultural economy and the simple fact that the majority of land would already have been treated by this time.

In his country-wide assessment of nineteenth century underdrainage Phillips (1989) presents a series of maps which show parishes in England that were subject to drainage rent-charge from loans taken to fund local underdrainage. Six maps are presented which cover the period 1847 to 1899. In the Yorkshire area it appears that a large number of drainage schemes were initiated between 1850 and 1859 (figure 6.4), particularly in the piedmont reaches of the River Swale, and throughout the Vale of York Figure 6.5 shows the extent of rentcharges upto 1899 and shows a similar geographical distribution in the Ouse basin. There is little or no evidence of the extent or distribution of underdrainage schemes from the late nineteenth century until the introduction of government grant-aid in 1939, although in general this period was one of agricultural depression and relatively little drainage activity. After 1939 statistics on the area of land drained annually are available for England and Wales, although unfortunately not at the county or parish level. As previously discussed the area of land drainage has increased from 1939 to a peak in the 1970s (figure 6.6). Between 1971 and 1980 Robinson (1990) has mapped the geographical distribution of underdrainage on agricultural land in England and Wales and suggests that around one million hectares have been drained over this decade. Figure 6.6 shows that the majority of the areas that were drained over this period were in the south and east of England. With respect to the Yorkshire Ouse basin, the majority of underdrainage has been concentrated in the southern part of the Vale of York. No statistics are available after 1980 although it is generally accepted that the level of drainage activity has declined since the peak of the 1970s.

***Figure 6.4** : Parishes subject to draining rentcharge, 1850-1859. (from Phillips, 1989)*

***Figure 6.5** : Parishes subject to draining rentcharge, 1890-1899. (from Phillips, 1989)*

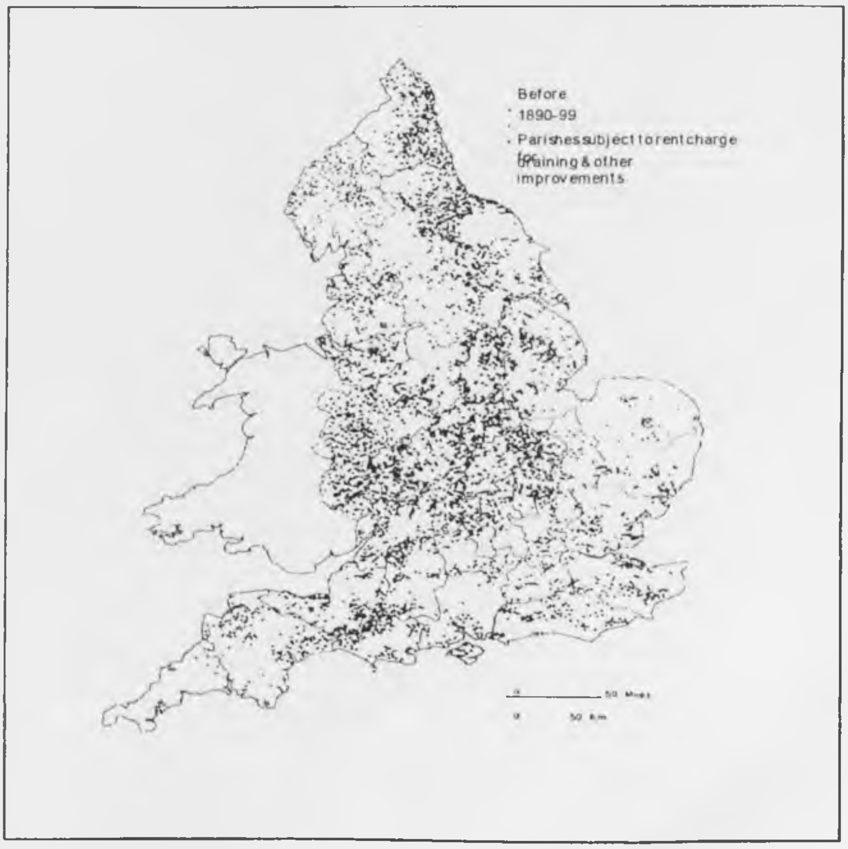
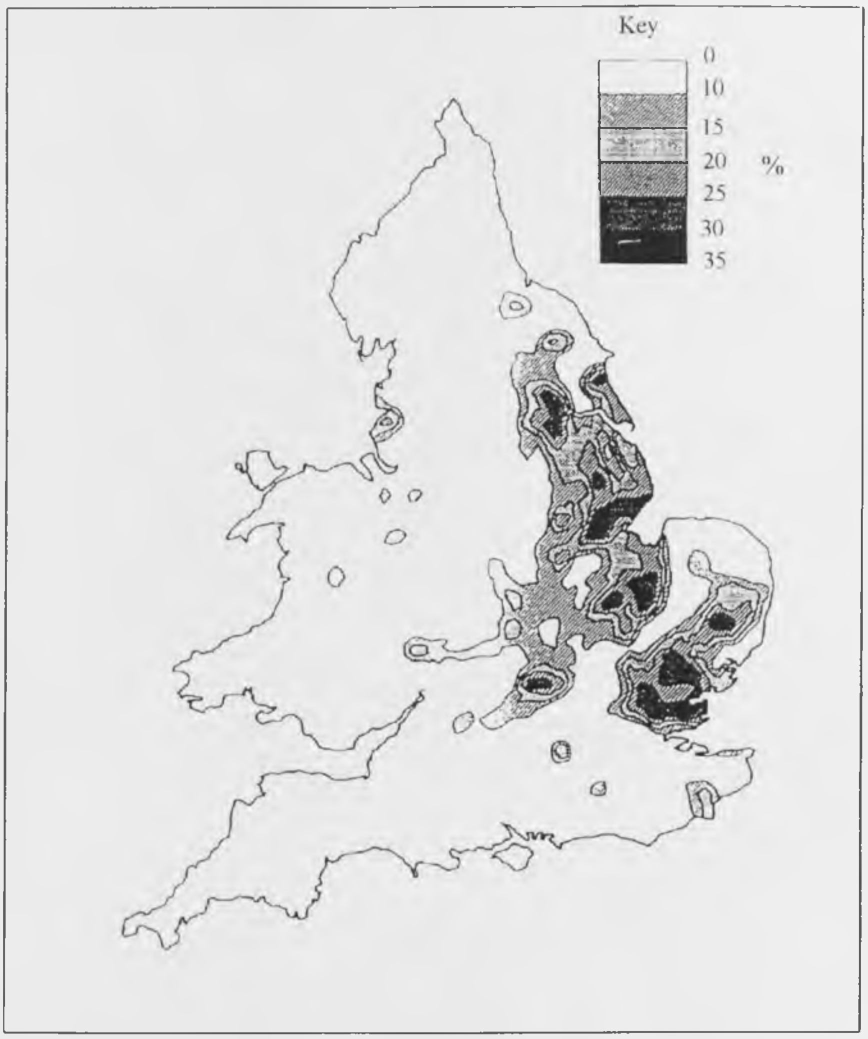
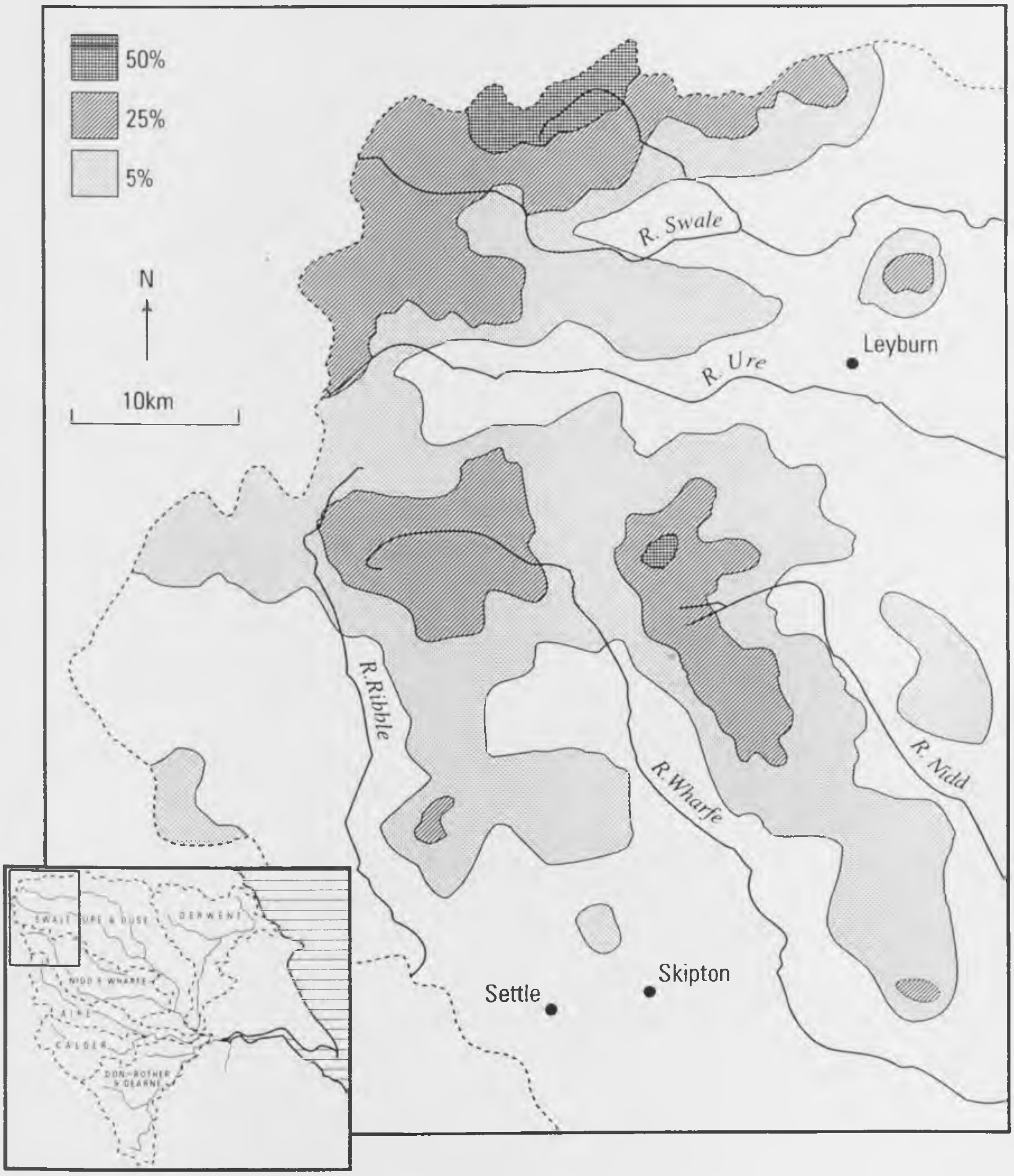


Figure 6.6 : *Percentage of agricultural land in England and Wales underdrained in the period 1971-80 (from Robinson, 1990)*



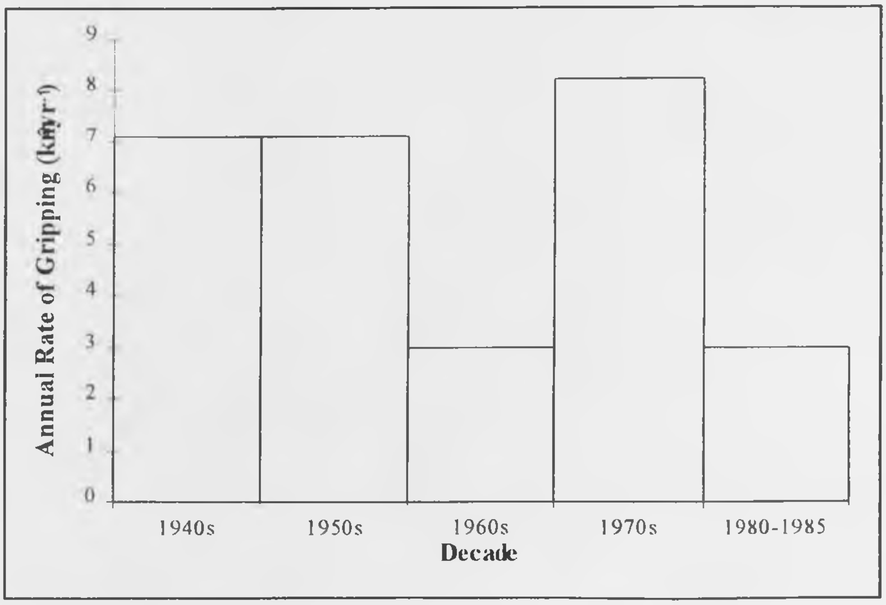
The drainage schemes considered so far have all related to the underdrainage of agricultural land in Yorkshire. Hill drainage in upland areas in the form of moorland gripping (see chapter 3) can also significantly affect peak flows. To recap, moorland gripping is the cutting of open ditches into areas of moorland in an attempt to improve the land for sheep grazing and grouse. Robinson (1990) has conducted the only detailed survey of the timing and extent of moorland gripping in the Yorkshire Dales area, where it has been suggested that this practice may have exacerbated flooding at York and Selby (Oldfield, 1983). Figure 6.7 shows the percentage of land in the Yorkshire Dales which has had moorland gripping between 1940 and 1985. Robinson suggests that the most heavily gripped areas (>50% of the land) are in the upper reaches of the River Nidd, and in Arkengarthdale which is a tributary of the River Swale. The headwaters of all the major northern tributaries in the Ouse basin have been subject to gripping to some extent, large areas where over 25% of the land has been gripped occur not only on the

Figure 6.7: *Percentage of land in the Yorkshire Dales which had moorland gripping 1940 – 1985. (after Robinson, (1990)*



Nidd and Swale, but also on the Ure and Wharfe. Robinson (1990) has also estimated the timing of moorland gripping based on MAFF grand-aid records, which is shown in figure 6.8. Although this diagram only gives a crude decadal estimate of the annual rate of moorland gripping it does provide a basis for comparison with variations in the flood record. Large-scale gripping was initiated in the Yorkshire Dales in the 1940s as a result of the introduction of grant-aid and the greater need for livestock production after the Second World War. The Cuthbertson drainage plough was also introduced around this time which improved on existing methods of gripping (Thompson, 1948). This rate of drainage continued into the 1950s which were followed by a significant decline in the 1960s Rates of drainage increased markedly in the 1970s and declined in the 1980s to very low levels at present Robinson (1990) suggests this recent reduction in moorland gripping is due to the fact that MAFF no longer encourages hill drainage of this kind. Indeed recent concerns about the effects of gripping on downstream flooding and the erosion of gripped ditches resulted in a BBC documentary entitled 'All washed out' as part of the Close Up North series. It is probably a combination of these recent concerns, and the realisation that gripping does not significantly improve vegetation that has resulted in the cessation of this practice in recent years.

Figure 6.8 : *Rate of moorland gripping in the Yorkshire Dales (re-drawn from Robinson, 1990)*



6.4. CHANNELIZATION IN THE YORKSHIRE OUSE BASIN

6.4.1. Introduction

River Channelization 'may be defined as the modification of river channels for the purposes of flood control, land drainage, navigation and the reduction and prevention of erosion' (Brookes *et al.*, 1983, p97). Methods of channelization and their effects on flooding are considered in Chapter 2, however, channelization can include resectioning, realignment, channel diversions, embankments, bank protection and general maintenance works (Brookes, 1985). The hydrological consequences of channel works may be to prevent local flooding but to increase flood levels downstream. At the drainage basin scale one of the most important consequences of channel improvement works may be to alter the timing of peak flows in tributary streams, which can either increase or decrease the flood peak in the main channel (Brookes, 1985). The effects of channelization schemes depends on the length of river involved and channel characteristics, such as the degree of meandering. Channelization does not include channels that are completely artificial, such as the drains and ditches constructed for farm drainage, nor does it include man-made structures within the channel such as weirs.

The main aim of this section is to assess the spatial and temporal patterns of channel works in the Ouse basin which may have affected flood levels. The major areas considered are the construction of flood embankments, major channel improvement schemes, flood defences and washlands (natural and controlled).

6.4.2. History of river management organisations in the Yorkshire Ouse basin

Although channel modification has been practised for at least five centuries (Johnson, 1954. cited in Brookes *et al.*, 1983) it was not until the late 1920s that concerns were voiced as to the poor management of land drainage and flood control in England and Wales. The River Ouse (Yorkshire) Catchment Board was originally set-up in 1922 following the promotion of Local Bills by West Riding County Council to control land drainage (Sheail, 1997). The River Ouse (Yorkshire) Catchment Board was 'reconstituted' (Sheail, 1997) in 1931 following the Land Drainage Act of 1930 which established 46 Catchment Boards in England and Wales, and integrated the management of flood control and land drainage for the first time (Brookes *et al.*, 1983). These authors suggest that the Act of 1930 resulted in 'a period of intense activity involving substantial lengths of river' (Brookes *et al.*, 1983, p105). In 1951 the River Ouse (Yorkshire) Catchment Board was superseded by the Yorkshire Ouse River Board under the River Board Act of 1948, which was itself superseded by the Water Resources Act of 1963 which established 29 river authorities in England and Wales. The Yorkshire Ouse and Hull

River Authority operated between 1965 and 1974 until the inauguration of the Yorkshire Water Authority which was established after the Water Act of 1973, and formed part of 10 regional water authorities in England and Wales. More recent river management has been controlled by the National Rivers Authority between 1989 and 1996, and the Environment Agency since April 1996.

6.4.3. Data sources

Information relating to the timing, location and extent of channel improvement schemes has been extracted from a number of sources. Schemes undertaken by the various river management organisations outlined above are described in their annual reports. These reports contain a wealth of information relating to the incidence of flooding, climate characteristics for the year, as well as completed and proposed capital works and maintenance schemes. The majority of information relating to works completed on each major Ouse tributary is far too detailed and generalised to be used in this study, usually relating to routine channel maintenance in small areas. Typically, records detail works such as the seasonal mowing of flood banks, minor flood bank restoration and repairs, vermin trapping, the removal of gravel shoals, and the clearance of impeding vegetation within the channel. However, some reports do contain detailed records of major improvement schemes. Extracting this information would be a lengthy and time consuming task since the reports often detail work completed in small areas for that particular year. Fortunately, summaries of the timing of all major channel improvement schemes in the Yorkshire Ouse were obtained from the Yorkshire Water Authority in 1980 by Dr Andrew Brookes for a paper investigating the extent of channelization in England and Wales (see Brookes *et al.*, 1983), and have been supplied for this project. Information detailing the contemporary situation in the catchment, particularly relating to the location and scale of flood defence schemes, has been extracted from the consultation reports of NRA Catchment Management Plans which were completed around 1994.

6.4.4. Major channel improvement schemes and flood defences

6.4.4.1. Early channel embankment schemes and flood defences

The River Foss Flood Alleviation Draft Report (Mott, Hey & Anderson and Sir M Macdonald & Partners, 1982) investigated historical records relating to flood embankment schemes both upstream and in the City of York. No records of any large-scale schemes were discovered over the past 100 years, however the report does concede that the building and maintenance of flood embankments would have been a continuous process over many years. Evidence for flood embankment schemes in York itself does exist, several authors (e.g. Farrant, 1953; Radley and

Simms, 1971) suggest that both the Romans and Saxons built embankments in the city. It was not until the 12th and 13th centuries that evidence of embankments around York exist, when commissions were made for bank maintenance. This evidence must be regarded with some caution since there is no indication of the original source. Farrant (1953) discusses periods when embankments were likely to be widely extended to other areas of the Ouse catchment. For example, there was an increase in demand for agricultural produce during the Napoleonic Wars, meaning that low lying agricultural land would have had to be protected from flooding.

Major land drainage work was being carried out on the lower River Don as early as the seventeenth century. Cornelius Vermuyden drained the low-lying land to the east of Doncaster between 1626 and 1630. Firth (1997) gives a detailed account of this work. Prior to any artificial alterations the Don split into three channels near Thorne, two of which drained into the River Trent and one into the Aire. The channels leading to the Trent were blocked and the entire flow diverted into the Aire. Unfortunately for Vermuyden this caused flooding of land which had not been affected prior to the diversion. To solve the flood problem an artificial flood relief channel was cut between New Bridge, near Rawcliffe and the Ouse at Goole. After a large flood the river began to permanently flow down the flood relief channel (known as the Dutch River), and the branch to the Aire silted up. Firth (1997) suggests that between the completion of this work and the late nineteenth century, few channel improvement and flood defence works were carried out. In the late nineteenth century the raising and strengthening of flood banks around Doncaster was initiated by the Dun Drainage Commissioners, and several controlled over-spill flood relief channels constructed, such as that at Black Pond which has operated during the floods of 1886, 1892, 1931, 1932 and 1947.

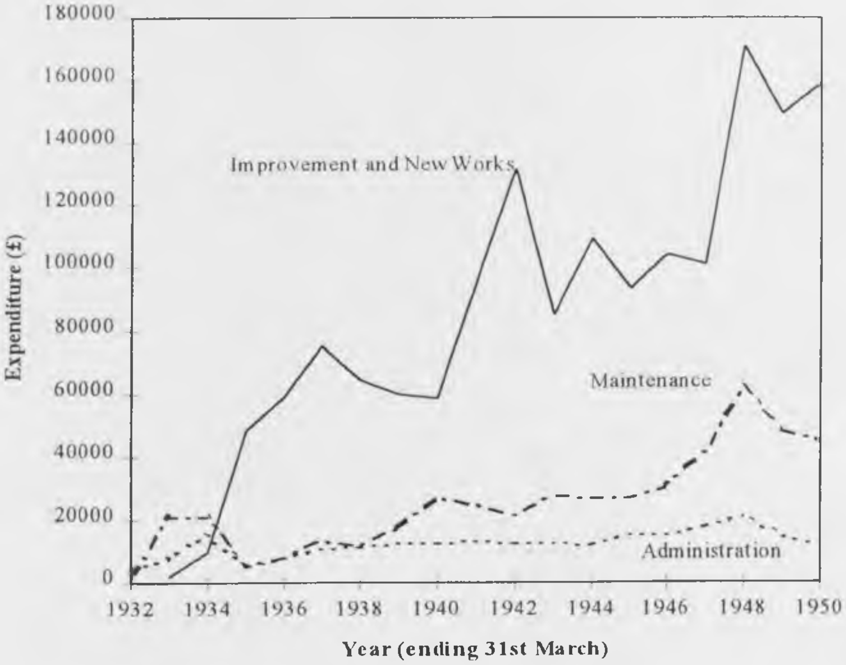
After this time the first record of a catchment wide increase in flood embankment construction or at least maintenance of embankments, is in 1930 following the Land Drainage Act which resulted in the cost for maintenance of flood embankments being raised from the community as a whole rather than the individual riparian land owners. On the Aire and Calder the river has been embanked by ‘successive generations of landowners’ (Pellymounter & Falconer, 1992, p187.) and has consequently developed a complex system of washlands.

Clearly it is difficult to establish the timing and scale of past channel embankment schemes. Although it is likely that embankments have been in place prior to the start of gauged flood records. After this time records of channel works improve and the timing and scale of improvement schemes can be assessed.

6.4.4.2. Major improvement schemes in the Ouse basin since 1931

Annual expenditure of the River Ouse (Yorkshire) Catchment Board between 1932 and 1950 is shown in figure 6.9. This gives us an indication of the scale of investment over time in three areas of the Board's main activities, channel improvement and new works, maintenance of the channel and flood banks, and administration costs.

***Figure 6.9** : Annual expenditure of the River Ouse (Yorkshire) Catchment Board 1932-1950*



Redrawn from Clark and Simpson (1964)

Several years after the establishment of the Catchment Board the majority of capital was spent on channel improvement and new works, this investment increasing markedly over the whole period, and particularly since the Second World War. Expenditure on channel maintenance and administration has also increased over this period, although not as rapidly. The location of major improvement schemes between 1934 and 1980 is shown in table 6.1. The majority of these schemes were not initiated until the 1960s, although exceptions include the River Don Improvement Scheme which commenced in 1934.

***Table 6.1** : Major river improvement schemes in the Ouse basin 1934-1980*

River / Area	Date of Scheme
Sea Cut (Artificial watercourse constructed 1800-1810)	1955-1975
Upper River Derwent and River Hertford	1950-1978
Rivers Rye, Severn, Dove & Riccal	1948-1979
Costa Beck	1954-1955
Lower River Derwent	1951-1974
River Foss	1970-1980
River Aire	1965-1980
River Calder and tributaries	1965-1980
River Don	1934-1978
River Dearne	1960-1980
River Rother	1960-1975
River Went	1960-1980
Ea Beck (tributary of the River Don north of Doncaster)	1960-1980

(This information was supplied by Dr Andrew Brookes of the Environment Agency Original source was Mr Savage of the Yorkshire Water Authority - Rivers Division dated 3rd December 1980.)

***Table 6.2** : Channelization on the River Don upto 1976 (Work carried out by Yorkshire Water Authority and predecessors)*

Location	Date	Details of improvement
Goole to Doncaster	1934-1962	Enlargement and embankment lining
Rawcliffe Bridge (Dutch River)	1964-1965	Protection / embanking
Sykehouse Landing	1966-	Protection / embanking
Swinton	1966-	Embanking / realignment
Swinton	1967	Protection / dredging
Goole	1968	Bank protection
Goole - New Bridge	1968	Raising banks / protection
Upstream of New Bridge	1968	Stone revetment
Thorne Workshop	1968	Stone revetment / realigning
Long Sandhall	1968	Protection
Swinton	1970	Embankment
Sprotborough Ings	1970	Dredging / embankment
Rotherham	1971	Embankment / flood wall
Rotherham	1972	Embankment / protection
Kilnhurst	1976-	Enlargement

(This information was supplied by Dr Andrew Brookes of the Environment Agency. Original source was Mr Savage of the Yorkshire Water Authority - Rivers Division dated 3rd December 1980.)

The River Don has been subject to a large number of channelization schemes which are summarised in table 6.2 . Many of these works have been conducted in the tidal reaches between Doncaster and Goole, however this area still needs to be considered since the main flood gauging site on the Don is at Doncaster. After the completion of the lower Don improvement scheme in the early 1960s attention was turned to areas of river upstream of Doncaster. Controlled washlands were constructed above Doncaster on the Rivers Don, Rother and Dearne. Washlands were formalised on the River Rother from the late-1950s at Cranklow, Treeton and Woodhouse Mill, and on the Dearne from the early-1960s, at Dearne Mouth, Harlington, North Ings, Bolton upon Dearne, Wombwell Ings, Darfield, Houghton and Cudworth.

In summary, the majority of improvement schemes between the 1930s and 1980 were carried out on the southern industrialised and heavily populated rivers of the Aire, Calder and Don. A number of schemes have also been carried out on both the upper and lower Derwent since the 1950s. In contrast there is a notable absence of major improvement schemes on the northern Ouse tributaries including the Swale, Ure, Nidd, and Wharfe.

6.4.4.3. Contemporary flood defences and washlands

Whilst information relating to past river improvement and flood defence schemes is often difficult to obtain, an assessment of contemporary flood defences is a relatively straight-forward task which indicates the cumulative extent of past schemes. The information summarised below has been extracted from National Rivers Authority Catchment Management Plan Consultation Reports, and Firth (1997) for the River Don. An overall summary is given in table 6.3, which details the length of ‘main river’ (where the Environment Agency ‘can control all activities on the protected bank-side land and undertake improvement and maintenance works’ (NRA, Ndb, p60.)) and flood defences, and the people and property protected in house equivalents. In this table the number of house equivalents protected per kilometre of main river has been calculated, and clearly shows the highest values to be on the southern Ouse basin rivers, particularly the Calder, Aire and Don. This is simply indicative of the fact that these rivers flow through highly populated and industrialised areas, whereas the Swale, Ure, Nidd and Wharfe for example flow through rural farming areas.

This section details the location and type of flood defences in each Ouse tributary, which have been sub-divided according to Catchment Management Plan divisions (i.e. Swale, Ure and Ouse; Nidd and Wharfe; Aire; Calder; Don, Dearne and Rother; Derwent). Maps showing the

Table 6.3 : *Length of Main River and house equivalents protected by flood defences*

River(s)	Length of designated 'Main River' (km)	Length of flood defences on Main River (km)	People and property protected (House equivalents)	House equivalents protected per km of Main River
Swale, Ure and Ouse	311	244	6600	21.22
Nidd and Wharfe	255	52	2800	10.98
Aire	148	95	5700	38.51
Calder	109	169	6969	63.94
Don, Rother and Dearne	264	180	7440	28.18
Derwent	264	210	3245	12.29

Source : *NRA Catchment Management Plans* location of flood defences and washlands have been redrawn from Catchment Management Plans and are shown in Appendix D.

(a) River Derwent - *(Source : NRA (Ndb); See map in Appendix D(i))*
The majority of main river on the Derwent is embanked on one or both sides protecting arable land in the upper reaches and small town such as Stamford Bridge in the lower reaches. In the middle reaches of the Derwent between Malton and Stamford Bridge there are no major flood defences. Below Stamford Bridge extensive flood embankments have created large washland areas such as Wheldrake Ings, Ellerton Ings and North Duffield Carrs. In the early nineteenth century the 'Sea Cut' was constructed on the upper Derwent which is a totally artificial, man-made channel, which diverts flood flows from the Derwent headwaters, via a sluice, directly into the North Sea

Other large-scale man-made features on the Derwent include Barmby Tidal Barrage and lock situated at the confluence with the Ouse. This barrage is used to reduce peak surge tide levels at flood prone towns such as Selby. Under high tide and tidal surge conditions the barrier on the Derwent is opened to allow the tide to enter the lower reaches of the Derwent.

(b) Rivers Swale, Ure and Ouse - *(Source : NRA (Ndc); See map in Appendix D(ii))*
Flood embankments on the River Swale extend from Catterick to the confluence with the Ure. Washland areas are the main form of flood defence and are used to store flood water when the embankments have been over-topped. The main washlands on the Swale are situated at Morton, Myton and Ellenthorpe. The Ure is embanked in isolated sections, particularly around Wensley, Jervaulx, Nunwick and Newby, with major washlands in the lower reaches around Aldborough and Nunwick. Boroughbridge is situated at the confluence of the Swale and Ure and a major flood defence scheme was completed in 1988. However, the town was flooded in 1991 when Aldborough Ings bank was over-topped. This bank has subsequently been raised to a 100-year return period protection level. Downstream of Boroughbridge major washlands are located at Linton-on-Ouse and around the City of York.

Flood defences in and around York

The second largest flood on record at York occurred in 1947 (peak stage of 9.96m AOD) and caused £100 000 worth of damage and affected in excess of 1000 buildings. Similarly, the largest event on record (peak stage of 10.12m AOD) in 1982 flooded some 70ha of land in the eastern part of the city along the River Foss, Tang Hall Beck and Osbaldwick Beck due to the Ouse 'backing up' the River Foss. Estimates suggest that this single event caused £2 million worth of damage. It was floods such as 1982, 1947 and 1978 which prompted the building of York`s major flood defences such as the Foss barrier and North Street schemes.

The Foss Barrier

In the past most of the widespread flooding in York occurred directly adjacent to the River Ouse and along the River Foss and its tributaries. Prior to construction of the Foss barrier, the River Foss had sufficient capacity to carry stormwater up to the 100-year flood (Miles, 1987). The normal water level of the Foss was 7.6m AOD which is 2.6m above that of the Ouse, this being due to the lock at Castle Mills Bridge. Once the water level exceeded 7.6m AOD the water backed up the Foss and often caused flooding. It was for this reason that the Foss Barrier was built, feasibility studies being carried out in 1982 and the barrier completed in 1988 at a total cost of £3.63million. The defence level of the barrier is 10.45m AOD.

Other defences around York

The City of York now has widespread flood defences, however, Arnold (1995) points out that it was not until after the floods of 1978 and 1982 that state funding became available for flood amelioration schemes in urban areas. In the city itself there are a number of flood defence schemes, for example around Acomb Landing, Leeman Road, North Street and Lower Ebor Street where earth embankments and brick or atone clad wall are common. The extensive washland area of Clifton Ings is around 2km upstream of Lendal Bridge and is controlled via flood gates built into the river banks. By flooding this area the water level at York can be reduced by up to 150mm, and when full the Ings can hold around 2 million cubic metres of water (NRA, Ndc).

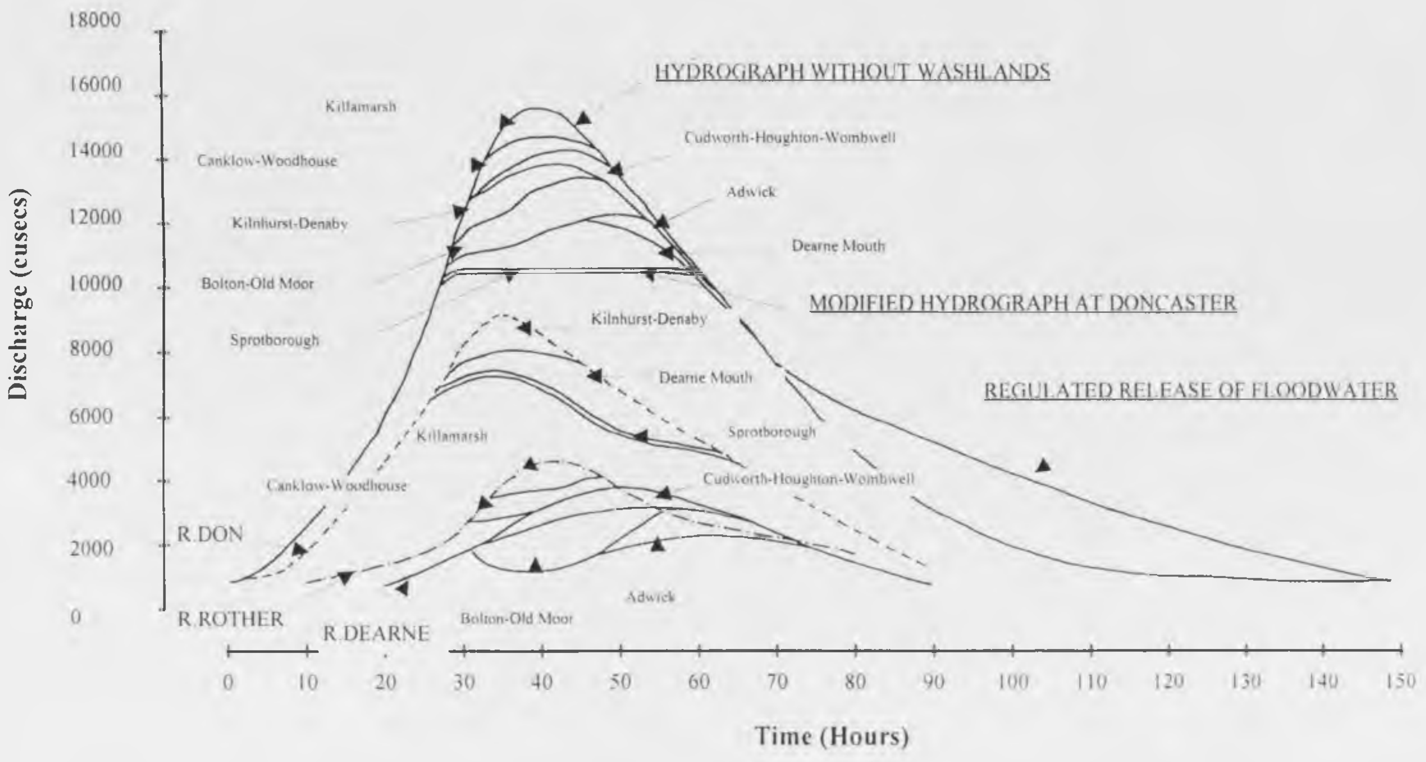
(c) Rivers Nidd and Wharfe - *(Source : NRA (1994); See map in Appendix D(iii))*

There are no major urban flood defences on the Nidd, however there are extensive embankments from around Knaresborough to the confluence with the Ouse creating large washland areas. As discussed in section 6.5.1., Gouthwaite reservoir can be drawn-down to reduce peak flows and help alleviate downstream flooding. Downstream of Ilkley on the River Wharfe there are extensive natural washlands, particularly around Pool and Newton Kyme. Major controlled washlands have being formalised around Tadcaster and Ryther.

(d) River Aire - *(Source : NRA, (1993); See map in Appendix D(iv))*

The upper Aire has been extensively embanked, creating large areas of washlands, particularly downstream of Keighley. Controlled washlands have also been constructed around Skipton, Cononley and Kildwick. Downstream of Leeds a number of controlled washlands have been

Figure 6.10 : Flood hydrograph of the Don, Dearne and Rother - the influence of washlands (redrawn from Firth (1997))



constructed over the past thirty years, including, St. Aidans, Fairburn Ings, Knottingley Ings, Eggborough Ings and Snaith Ings.

(e) River Calder - *(Source : NRA (Nda); See map in Appendix D(v))*

On the Calder both controlled washlands and major flood defence works have been implemented to address the problem of flooding, which is 'mainly a legacy of the industrial revolution' (NRA, Nda, p53.). Due to the steep valley sides there are relatively few washland areas on the Calder upstream of the confluence with the River Colne near Huddersfield. Below Huddersfield controlled washlands have been constructed in the areas around Wakefield, Altofts, Methley and Castleford. A large number of channel improvement and flood defence schemes have also been implemented on the Calder around. Todmorden. Mytholmroyd, Sowerby Bridge, Copley, Elland, Brighouse, Dewsbury, Horbury, Wakefield and Methley.

In recent years a great deal of capital has been invested in channel improvement and flood defence, schemes include the Dewsbury area between 1988 and 1998 with an estimated cost of £16 million, on the River Spen 1986 to 1997 (estimated cost of £3.7 million), and in the Fenay Beck area (cost of £4.6 million) (see Winders (1991)).

(f) River Don - *(Source : Firth (1996)).*

Since the mid-1980s the chief flood defence strategy on the River Don has been to improve the use of washland areas for flood control. It has been estimated that this improved operating strategy has reduced the risk of flooding at Doncaster from a 1 in 40 year flood to a 1 in 150 year flood (Firth, 1996) (see figure 6.10). On the upper Don flood protection works have been concentrated on tributary streams such as the River Sheaf (see Young and Cross, 1992). Similarly, since the late-1970s and early-1980s comprehensive improvement schemes have been carried out on the Rother and Dearne.

6.5. RESERVOIRS IN THE YORKSHIRE OUSE BASIN

The documented effects of reservoirs on flood peaks have been discussed in Chapter 2 and include the attenuation of flood peaks due to storage of a portion of the flood flow and the de-synchronisation of tributary and mainstream peaks (Petts, 1984; Higgs & Petts, 1988; Petts & Lewin, 1979). The downstream impact of reservoirs depends on a number of factors, namely location of the reservoirs within the catchment, the frequency and order of the tributary streams which are affected, the percentage area of the catchment that is impounded and the operational rules of the individual reservoirs. Most studies have investigated the downstream impact of individual reservoirs (e.g. Gregory & Park, 1974; Higgs, 1987a). When attempting to assess the effects of reservoirs on flood flows in the Ouse basin the situation is far more complex

Table 6.4 : Reservoir summary information for major Ouse tributaries

Tributary	Total Number of Reservoirs	Largest reservoir by Useable Capacity				Average Usable Capacity ($10^3 m^3$)	Average catchment area (km^2)	Number of reservoirs with catchment area >10 km^2	Number of reservoirs with Usable Capacity > 2000 $10^3 m^3$
		Name	Usable Capacity ($10^3 m^3$)	Catchment area (km^2)	Date of Construction				
Swale	3	Cod Beck	470	7.60	1953	218	4.46	0	0
Ure	3	Leighton	4955	22.88	1929	2594	12.55	2	2
Nidd	7	Scar House	9414	30.10	1936	3069	17.50	3	3
Ouse	13	Scar House	9414	30.10	1936	2301	13.00	5	5
Wharfe	9	Grimwith	21772	28.33	1984	5176	15.43	5	6
Aire	18	Lower Laithe	1235	4.37	1926	499	3.66	0	0
Calder	34	Scammonden	7420	20.90	1970	1287	4.19	2	6
Don	22	Winscar	7590	7.10	1975	2033	7.98	8	8

All Data from Yorkshire Water Plc.

since there are a large number of reservoirs which have been constructed in different areas of various sub-catchments and at different times. In some cases there are a series of reservoirs on a particular tributary when other areas remain relatively unaffected. Due to considerations such as this, and the large spatial scale being considered it is only possible to suggest the probable effects of reservoirs on downstream flood peaks based on parameters such as the total percentage of a catchment that is impounded. However, it is possible in some cases to examine flood data before and after a major construction project upstream of a gauging station and assess any attenuation effects. This is also not possible, for example the largest reservoir by catchment area in the Ouse basin is Gouthwaite on the River Nidd which drains an area of 50.87 km^2. The gauging station used for analysis in Chapter 4 was the Nidd at Hunsingore with a catchment area of 484.3 km^2. This reservoir alone impounds 10.5% of the total catchment area upstream of the gauging station. However, this reservoir was constructed in 1901 whereas flood data are not available on the Nidd until 1936. Occasionally the construction of a large reservoir has occurred in a period when flood records exist, for example, Grimwith reservoir in the River Wharfe catchment was built in 1984 and drains 3.78% of the catchment upstream of the gauging station at Flint Mill. Even so this is still complicated by the presence of other reservoirs in the catchment. Taking these limitations into consideration the main aims of this section are to assess (1) the location of reservoirs within Ouse basin sub-catchments. (2) the percentage area of a sub-catchment which is impounded by reservoirs. (3) the timing of reservoir construction. (4) any possible or discernible affects on flood records in the Ouse basin.

Data pertaining to reservoir location, date of construction, useable capacity and catchment area were obtained from Yorkshire Water Services Ltd. The data were sub-divided according to location within one of the major Ouse tributaries (Swale, Ure, Nidd, Ouse, Wharfe Aire, Calder, Don) to enable the area above each gauging station used for analysis in Chapter 4 to be calculated. Two of the gauging sites have not been considered, the Calder at Broadreach, since a reliable catchment has not been established, and the Derwent at Buttercrambe, since there are no significant reservoirs in the Derwent catchment.

6.5.1. Reservoir location and general information

The location of reservoirs in Ouse basin sub-catchments are shown in appendix E, these diagrams are based on National Rivers Authority Catchment Management Plan maps and therefore grouped according the their scheme. Table 6.4 summarises information on reservoirs within each individual catchment.

The River Swale (appendix E(i)) is natural to within 10% of the 95 percentile flow (IH gauging station summary sheets) and is relatively unaffected by reservoirs. The catchment contains only three small reservoirs in the Cod Beck area.

The River Ure also has three impounding reservoirs (appendix E(i)), although only of a moderate size they are larger than those on the Swale, with the largest being Leighton reservoir with a useable capacity (UC) of 4955 10^3m^3 and a catchment area (CA) of 22.88km^2.

Some of the largest reservoirs in the Ouse basin are located in Nidderdale (appendix E(ii)). Two of these large reservoirs, Scar House (UC = 9414 10^3m^3, CA = 30.10km^2) and Angram (UC = 4736 10^3m^3, CA = 14.65km^2) were constructed to supply water to the Bradford area. Further downstream Gouthwaite reservoir was built around the turn of the century to maintain flows for mill owners and other industrial uses. Compensation water releases from Gouthwaite are managed for a number of activities ranging from maintaining a water supply for fishing to the reduction of peak flows by providing flood storage capacity during winter months (NRA, 1994).

In the Wharfe catchment (appendix E(ii)) there are no impounding reservoirs on the Wharfe itself. Upstream of Bolton Abbey, Grimwith reservoir on the River Dibb is used for compensation flows and upper and lower Barden reservoirs on Barden Back are utilised for public water supply to Leeds and Bradford. In the Washburn Valley which joins the Wharfe downstream of Otley, there are four fairly large reservoirs also used for water supply, Thruscross, Fewston, Swinsty and Lindley Wood, all of which have a useable capacity exceeding 2900 10^3m^3.

There are eighteen impounding reservoirs in the Aire catchment (appendix E(iii)) mainly used for public water supply. These fairly small impoundment schemes are concentrated on the River Worth and Harden Back, and to the north-west of Bradford. None of these reservoirs have a catchment area exceeding 9km^2, and are not sufficient to meet the supply demands of the major industrial areas and conurbations downstream, therefore water is imported from the Ure, Nidd, Wharfe, Ouse and Derwent catchments both from reservoirs and river intakes.

The Calder catchment (appendix E(iv)) is characterised by a large number of small impounding reservoirs for water supply. Most are concentrated on the right-bank tributaries of the Calder and include the areas around Cragg Brook, the River Ryburn, Black Brook, the River Colne and the River Holme. Left-bank tributaries which are impounded include Hebden Water and

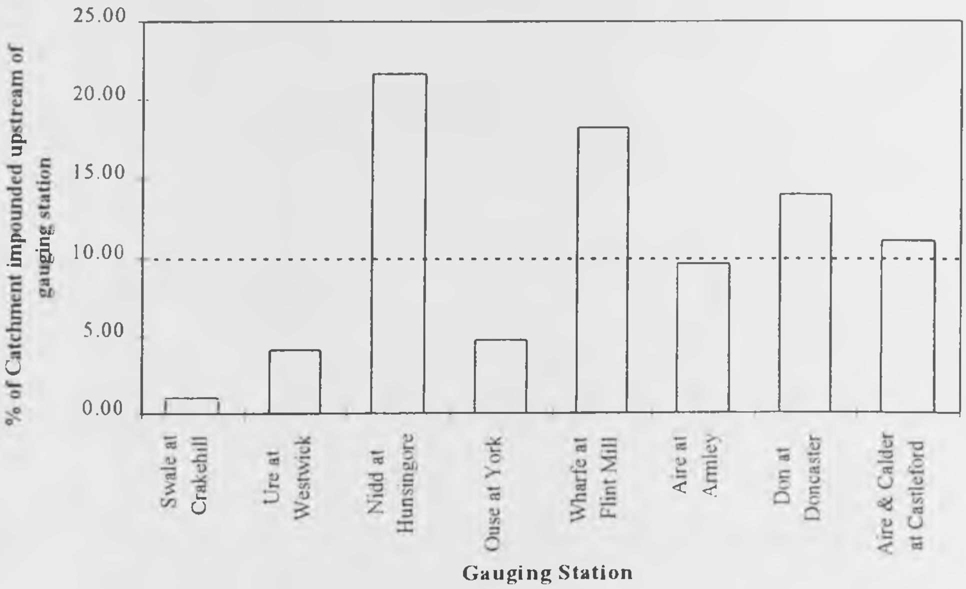
Luddenden Brook. A small number of reservoirs are also located further downstream on the Owler Beck to the south of Wakefield. In the Calder catchment only two of the thirty-four listed by Yorkshire Water have a catchment area greater than $10km^2$, these being Baitings and Scammonden.

In the Don catchment (appendix E(v)) the upper reaches are heavily reservoired for public water supply. The majority are concentrated upstream of Sheffield on the River Don, the Little Don, Ewden Beck, the River Loxley and River Rivelin. Eight out of the twenty-two reservoirs in the area have a catchment exceeding $10km^2$, the largest of which by area is Broomhead reservoir (UC = 4937 10^3m^3, CA = 21.96 km^2) built in 1934.

6.5.2. Percentage area of catchment affected by reservoirs

The next stage in this analysis is to assess the percentage area of individual catchments that are affected by impounding reservoirs upstream of the gauging stations where flood records have been analysed. Gregory and Park (1974) found that Clatworthy reservoir (CA = 18.2 km^2) on the River Tone had no significant affect on flows when less than 10% of the catchment area was reservoired. Although, the situation is more complex in the Ouse basin due to consecutive reservoirs in various tributaries and differences in the catchment areas of reservoirs, this figure has been adopted as an indicator to assess any possible effects of reservoirs on flood flows. Therefore taking the somewhat arbitrary value of 10% as being significant it would be expected that the affects of reservoirs would be greatest on the Nidd in terms of flood peak attenuation, since 21.68% of the catchment above the gauging station at Hunsingore has been impounded (see figure 6.11). Indeed, in Chapter 3 it has been shown that the flood peak of January 1982 was reduced on the Nidd due to reservoir storage. Noticeable affects may also be expected on the Wharfe, Don and Aire and Calder at Castleford, although the extent of this is unclear. Whereas it would be expected that the effects of floods would be relatively negligible on the Swale, Ure, Ouse and Aire (upstream of confluence with Calder). However, these simple conclusions are complicated by the fact that construction of reservoirs has varied through time, which will be considered in the next section.

Figure 6.11 : Total percentage area of catchment impounded upstream of gauging stations (dashed line represents 10% catchment area impounded)

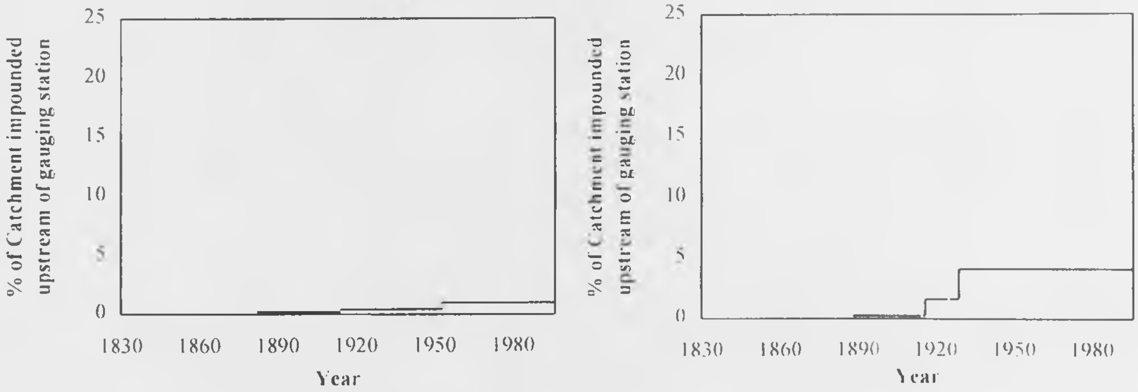


6.5.3. The timing of reservoir construction

Petts (1984) suggests that the major period of reservoir construction in the UK did not begin until the early 1900s, which coincided with advances in concrete and earth moving technology However in western Europe high rates of dam construction were experienced between 1840 and 1880, and in particular between 1900 and 1940, with the majority of impoundment schemes prior to the 1950s being relatively small.

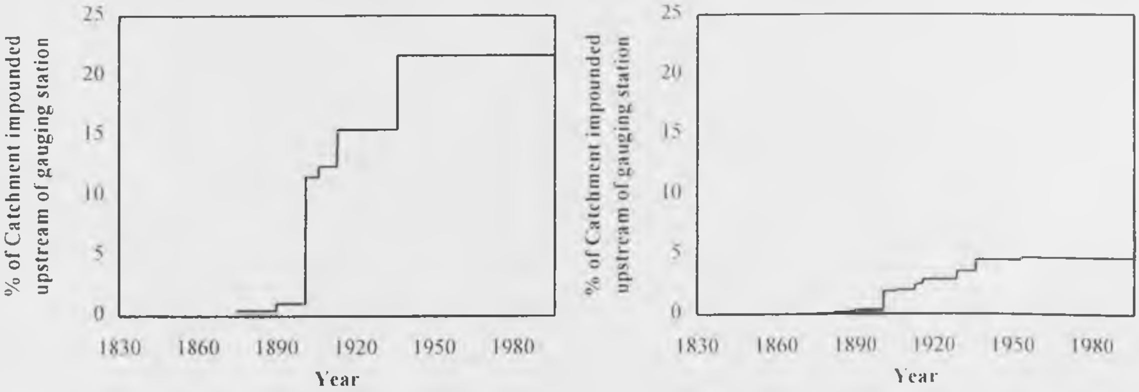
Figure 6.12 shows the cumulative percentage area of catchment upstream of each gauging site that was impounded by reservoirs over time. As discussed above, the catchments which are most likely to have been significantly affected are the Nidd, Wharfe, Don and the Aire and Calder catchments when combined. On the River Nidd all the reservoirs were built between the late nineteenth century and 1936, the largest of these being Scar House (1936), Gouthwaite (1901) and Angram (1913). Six relatively small reservoirs draining a total area of 77.79km^2 were constructed in the nineteenth century on the Wharfe, and three in the twentieth century draining an area of 61.08km^2. Two of the largest schemes were Thruscross reservoir in the Washburn Valley built in 1966 and Grimwith on the River Dibb built in 1984. The two remaining catchments where reservoirs may have a significant effect are the Aire and Calder combined, and the River Don. These catchments show a much different pattern in the timing of reservoir construction. In the Aire and Calder catchments the reservoirs built in the late nineteenth century and early twentieth century were comparatively small when considering

Figure 6.12 : Cumulative percentage area of catchment impounded upstream of gauging stations



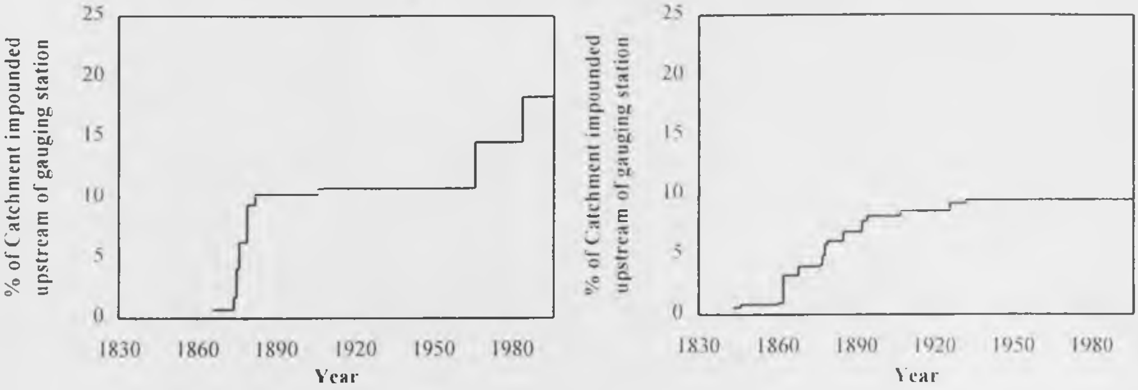
(a) : Swale at Crakehill

(b) : Ure at Westwick



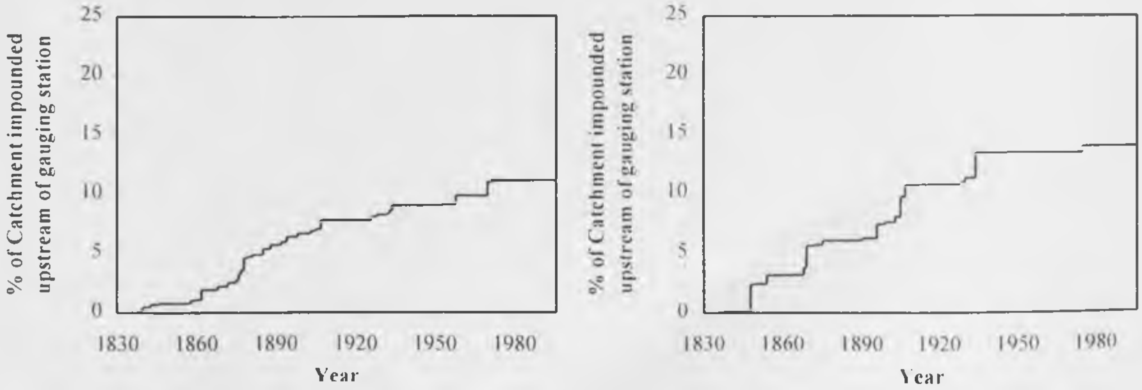
(c) : Nidd at Hunsingore

(d) : Ouse at York



(e) : Wharfe at Flint Mill

(f) : Aire at Armley



(g) : Aire & Calder at Castleford

(h) : Don at Doncaster

those on the Nidd for example. Between 1838 and 1907 forty-two impounding reservoirs were constructed in the Aire and Calder catchments, giving a total UC of 28301 10^3m^3 and draining a total area of 143.69km^2. The largest reservoir constructed in this period was at Blackmoorfoot in 1876 (UC = 2968 10^3m^3; CA = 8.12km^2). Slightly larger reservoirs were built after this time, for example between 1908 and 1971 ten reservoirs were built with a combined UC of 24432 10^3m^3, draining an area of 60.50 km^2 Clearly, the total UC of these reservoirs over the two periods is very similar, yet far fewer were constructed in the latter period reflecting the change to building larger reservoirs A similar trend in construction is evident on the River Don. Between 1938 and 1907 seventeen reservoirs were built with a total UC of 28480 103m3 and a drainage area of 134.78 km2. Some of these reservoirs were relatively large, such as Damflask built in 1896 (UC = 5106 10^3m^3; CA = 15.17km^2) and Langsett built in 1905 (UC = 5492 10^3m^3; CA = 21.06 km^2). Only five reservoirs were built between 1928 and 1975 with a total UC of 16245 10^3m^3 draining an area of 40.84 km^2.

6.6. SUMMARY OF LAND-USE HISTORY AND LINKS TO FLOOD RECORDS

This section aims to summarise three main aspects of land-use change. First, the possible effects of individual land-use changes on flooding, second, the spatial and temporal patterns of land-use change in the Ouse basin, and third, any relationships with observed variations in flood records. However, disentangling the relative importance of individual land-use changes in such a large basin is complicated by possible 'averaging effects' of different land-uses which may mask variations caused by individual treatments (Higgs, 1987a). Given these difficulties, and the further complications introduced by climatic variation (see Chapter 5), the relationships suggested here are simply based on examination of the timing of large-scale changes in land-use, and any associated variation in flood records which cannot be fully explained by a climatic hypothesis (for example, variations in flood records caused purely by climatic factors would be expected to result in a synchronous response throughout the basin, whereas it is unlikely that land-use changes would cause such a response since treatments are often localised.)

Agricultural land-use change

Different agronomic practices have been shown to affect runoff from agricultural land. Experiments suggest that rates of runoff are highest from heavily grazed pasture, and also from bare ground (e.g. recently ploughed), although ploughing may reduce runoff when compared to unploughed land by providing a rougher soil surface. The lowest rates of runoff were experienced on ungrazed land, such as temporary grassland and cereals (Heathwaite *et al.*, 1990). Intensification of farming has also been cited as a cause of increase runoff and erosion on farmland, and includes practices such as the removal of field boundaries to enlarge fields, and more intensive use of large farm machinery which can compact soils (Evans, 1990). Furthermore, a shift to the growing of 'winter cereals' has also been cited as the cause of increased runoff and erosion in areas such as the South Downs (Boardman, 1990; 1995), since the soil surface is often left bare and unprotected in wet winter months.

Temporal patterns of agricultural land-use in the Ouse basin reflect those experienced generally in England and Wales. There was a period of agricultural prosperity between the 1880s and the mid-1870s, known as the 'high farming era' This was a time of agricultural intensification, increasing arable area, and high rates of field underdrainage There followed a period of depression, from the 1870s until World War I during which time many arable areas reverted back to grassland and pasture. During World War I there was a short period of increased food production and hence arable area. The inter-war period was again one of depression when many arable areas reverted back to grassland. With the onset of World War II came the need for increased home food production, and arable area increased dramatically, to a level which has broadly been sustained to the present day.

Land drainage

The effects of land drainage schemes on peak flows is complex and has been shown to vary with soil type, climate and the type, extent and location of schemes within a catchment. Field-scale response to land drainage can be different from catchment-scale response, since at the catchment-scale, improvements to outfall and arterial channels must be considered, and the associated effect on flood peak synchronisation. In general, peak flows are higher from open ditches (e.g. moorland gripping) than from sub-surface pipe systems (underdrainage) with secondary treatments (e.g. moling and subsoiling), and peaks from the latter are higher than from sub-surface pipe systems alone. However, this does not necessarily imply that peak flows into arterial channels are increased by all types of drainage scheme. For example, at the field-scale, Robinson (1990) found that at wetter sites (i.e. soils with a high clay content and/or receive high rainfall) underdrainage reduces peak flows, whereas at drier sites (i.e. more permeable soils and/or receive low rainfall) drainage increases peak flows.

In the Ouse basin there was a period of intense underdrainage between 1840 and 1869 (Phillips, 1972; 1989) corresponding with the era of high farming. Most schemes at this time were concentrated in the piedmont reaches of northern rivers and in the Vale of York. The agricultural depression that followed (1880s-1930s) resulted in a marked reduction in drainage activity. In tandem with agricultural land-use change, a major increase in drainage activity was initiated around the time of the onset of World War II. Government grant-aid schemes were introduced around 1939 towards the cost of drainage systems, and resulted in a large increase in field underdrainage. Also around this time there was a major increase in hill drainage or 'moorland gripping' which will have undoubtedly increased rates of runoff in upland areas (although the extent and scale of downstream impacts are less clear). Much of this drainage activity was concentrated in the headwaters of the northern rivers, most notably in Nidderdale and Arkengarthdale (tributary of the Swale). The practice of gripping was ended in the 1980s, although by this time a large area of the Dales had been gripped, and as a result of severe erosion many of the drains have enlarged considerably, resulting in larger and more efficient runoff channels.

River channelization

River channelization schemes tend to reduce local flood levels, but often cause increased flood levels downstream (e.g. Emerson, 1971) by reducing floodplain storage capacity, and increasing flow velocities. As with other forms of land-use change, channelization may affect the synchronisation of flood peaks, though the extent of this is uncertain since the effects of individual schemes are only likely to persist for a few miles downstream (Heneage, 1951). Even so, it must not be assumed that channelization always results in increased downstream flooding (Keller, 1980).

There has been a long history of embanking in the Ouse basin, dating back to Roman times in the City of York. On the tidal section of the River Don there has been much historical drainage and channel alteration, principally by Vermuyden in the 1620s. Around Doncaster evidence from the late nineteenth century suggests that floodbanks were strengthened and raised, and a flood relief over-spill channel constructed (Firth, 1996). In general however, it is almost impossible to assess the time of embankment construction in much of the Ouse basin since it is likely that embanking has been carried out by 'successive generations of landowners' (Pellymounter and Falconer, 1992, p187) over many centuries. It was not until the 1930s, after the Land Drainage Act of 1930 and the establishment of the River Ouse (Yorkshire) Catchment Board, that intense activity began. The majority of channel improvement and flood defence schemes were initiated in the 1960s, and concentrated in the southern industrialised, and heavily populated areas (i.e. the Aire, Calder and Don catchments).

Reservoirs

Reservoirs can affect the magnitude and timing of flood events; flood magnitude may be reduced due to increased storage capacity provided by the reservoir, and flood peaks may be 'lagged', resulting in de-synchronisation of mainstream and tributary peaks. The effects of reservoirs diminish downstream, studies have suggested that the effects are evident until the impounded area is less than 10% of the total catchment area (Gregory and Park, 1974), and on the River Severn, the effect of Clywedog reservoir were discernible for around 40km downstream (Higgs, 1987a; Higgs and Petts, 1988). Reservoirs are most effective at reducing peak flows of small and moderate magnitude flood events, although the impact also depends on reservoir location, the proportion of the catchment impounded, and the operational rules of the reservoir.

In the Ouse basin a large number of reservoirs have been constructed in different sub-catchments and at different times, making the task of isolating the effects of individual reservoirs almost impossible. Only general trends may be identified in the timing, size and location of construction. Reservoirs on the Swale and Ure are few and small, and would not have any significant impact on flood flows at the gauging stations considered here. Whereas, on the Nidd there are three large reservoirs, including Gouthwaite which is used to reduce downstream peak flows by the Environment Agency. The total area impounded above Hunsingore on the Nidd is 21.7%, so we may expect some degree of peak flow reduction, although since all the reservoirs were constructed prior to flow gauging there is no way to investigate this. On the Wharfe there are four large reservoirs in the Washburn Valley, suggesting that lower peak flows may be expected from this part of the catchment. Two of the largest reservoirs in the Wharfe catchment were built during the gauging period, Thruscross in 1966 and Grimwith in 1984, which together impound 11.8% of the catchment area above the gauging station at Flint Mill. In the southern rivers there is a change in the character of impoundment schemes, reservoirs tend to be smaller and more numerous.

Land use change and links to flood records

To examine any relationships between changes in agricultural patterns and flooding the most suitable record to use is the Ouse at York, since this is a long, continuous record, and has a predominantly rural catchment area. One of the most striking trends in the record occurs around 1944 when there is a dramatic and sustained increase in flood frequency (the majority of which are of minor and moderate magnitude, i.e. $<Q_{10}$). This period coincides with a series of rapid land-use changes. First there is a marked increase in the area of arable land, and a decline in grassland area associated with the need for increased home food production in World

War II. There is also a marked rise in underdrainage schemes associated with this 'plough-up' campaign, and moorland gripping was widely practised in the Yorkshire Dales for the first time. Upland drainage almost certainly increased the rate of runoff from the uplands, although the effects of lowland drainage and increased arable area are more difficult to establish. We can say with some confidence however, that the combination of these changes significantly altered flood regime in the Ouse basin around this time.

A second relationship between changes in agricultural practices and flooding may also be evident. The most recent period, from the late-1970s onwards, has experienced the highest flood frequency and magnitude on record at several sites. Although climatic relationships have been suggested (Chapter 5), the increase in area under 'winter cereals' (see Evans and Cook, 1986) has also dramatically increase over this period, and has been linked to increases severe flooding in other areas of England (Boardman, 1990; 1995). This most recent period has also seen marked increase in grazing pressure, particularly in the Yorkshire Dales (Sansom, 1996). Sheep numbers have increased by nearly 40% since 1982, and Sansom has suggested that this may have contributed to recent severe flooding in Wensleydale, by promoting more rapid runoff through loss of vegetation cover and poaching of the soil. Furthermore, the cumulative affect of almost 50-years moorland gripping must be considered, since this would promote more rapid runoff from the upland.

In summary, it appears that a combination of increased upland and lowland drainage, and the conversion of grassland to arable land contributed to an increase in flood frequency on the Ouse at York. This is most probably due to increased rates of runoff from the uplands synchronising with downstream peaks. There also appear to be a link between increasing areas of winter wheat, increased grazing pressures and the cumulative effects of land drainage, and a marked increase in flood frequency and magnitude since the late-1970s.

Flood magnitude records for the rivers Aire, Calder and Don show different trends to those on northern rivers (unfortunately there are no long, continuous flood frequency records for the Aire, Calder or Don). Both the Calder at Broadreach, and the Aire and Calder at Castleford show highest flood magnitudes in the late nineteenth century (although these records only extent to 1968), after which time magnitude declined markedly, particularly on the Calder. This is most likely a consequence of channel improvement schemes initiated in the 1930s, which would reduce local flood levels, particularly in the built-up industrialised and heavily populated sections of river. A similar effect may also be evident on the Don, where a series of large floods between 1920 and 1948 prompted extensive flood defence schemes around the

Doncaster area, again reducing local flood levels. This is in contrast to the northern rivers where channelization schemes are not widespread.

Finally, considering the effects of reservoirs on flood flows is a difficult task given the variations in scale, time of construction and catchment areas of individual schemes. Catchments may have large numbers of reservoirs and isolating the effects of individual schemes is almost impossible However, a qualitative assessment suggests that the effects of reservoir may be discernible on the Nidd, Wharfe, and to a lesser extent on the southern rivers. On the Wharfe for example, there is some evidence of declining flood levels since the mid-1960s, not evident in other records This may relate to the construction of Thruscross (1966) and Grimwith (1984) reservoirs in the catchment.

CHAPTER 7

OVERVIEW :

River response to recent environmental change in the Yorkshire Ouse basin

There are two main aims of this summary chapter. First, to integrate records of flooding, climate and land-use change derived from the analyses in chapters, 4, 5, and 6, and suggest the principal factors that have influenced variations in flood frequency and magnitude over the past 900-years or so. Second, to examine the role of hemispheric-scale atmospheric circulation patterns in flood generation.

7.1 HYDROLOGICAL, CLIMATIC AND LAND-USE CHANGES IN THE OUSE BASIN 1263-1996

The following chronology integrates temporal and spatial variations in land-use, climate and flood hydrology since the eleventh century in the Yorkshire Ouse basin. The time period has been sub-divided according to hydrological characteristics (see table 7.1), based on an assessment of the timing of major changes in flood frequency and magnitude.

Gauged flood records allow for more detailed analysis than documentary records, and a higher degree of sub-division can be established. Consequently the chronology presented here is split into two main periods, one pertaining to the documentary record (1200-1899), and the other to the gauged record (1863-1996), although there is some degree of overlap (i.e. the period 1863-1899). Summary diagrams have been produced for both periods and show the principal variations in flood frequency and magnitude, climate and land-use where data are available.

Table 7.1 : Hydrological characteristics of sub-periods

Sub-period	Type of flood data	Hydrological Characteristics
1263-1360	Documentary	Series of large flood events recorded
1361-1549	Documentary	No documented floods
1550-1680	Documentary	High frequency of high magnitude floods
1681-1763	Documentary	Localised summer flooding in upland and piedmont regions
1764-1799	Documentary	High flood frequency and magnitude
1800-1849	Documentary	Moderate flood frequency and magnitude
1850-1899	Documentary and Gauged	High flood frequency and magnitude
1900-1915	Gauged	Very low flood frequency and magnitude
1916-1943	Gauged	Variation between sites. Generally increasing magnitude and very low flood frequency
1944-1968	Gauged	Dramatic and sustained increase in flood frequency. Variable flood magnitude
1969-1977	Gauged	Very low flood frequency and magnitude
1978-1996	Gauged	Very high flood frequency and magnitude

Figure 7.1 summarises the documentary period (1200-1899), and the data presented are based on the following information.

(1) Climate

(i) *Temperature* : The temperature graph presented shows 50-year averages of annual and winter temperatures in central England. Between 1200 and 1658 data have been derived from diarists and other documentary sources by Lamb (1977). Between 1659 and 1900 the homogenised Central England Temperature record (CET) (see Jones and Hulme, 1997; Parker *et al.*, 1992) is presented as a 50-year moving average (obtained from the Climatic Research Unit at the University of East Anglia).

(ii) *Rainfall* : Rainfall series show 50-year averages expressed as a percentage of the 1915-1950 average, of annual and September-June rainfall for England and Wales. Data between 1200 and 1768 are derived from Lamb (1977) from various documentary sources. Data between 1769 and 1900 are derived from the England and Wales Precipitation record (EWP) (see Gregory *et al.*, 1991; Jones *et al.*, 1997; Wigley and Jones, 1987; Wigley *et al.*, 1984), and expressed as a 50-year moving average (EWP obtained from the Climatic Research Unit at the University of East Anglia).

(iii) *Bog-surface wetness* High resolution proxy climate change evidence from Bolton Fell Moss in Cumbria was obtained from Barber *et al.* (1994). High DCA axis 1 scores represent dry periods, whilst low axis 1 scores represent wetter periods.

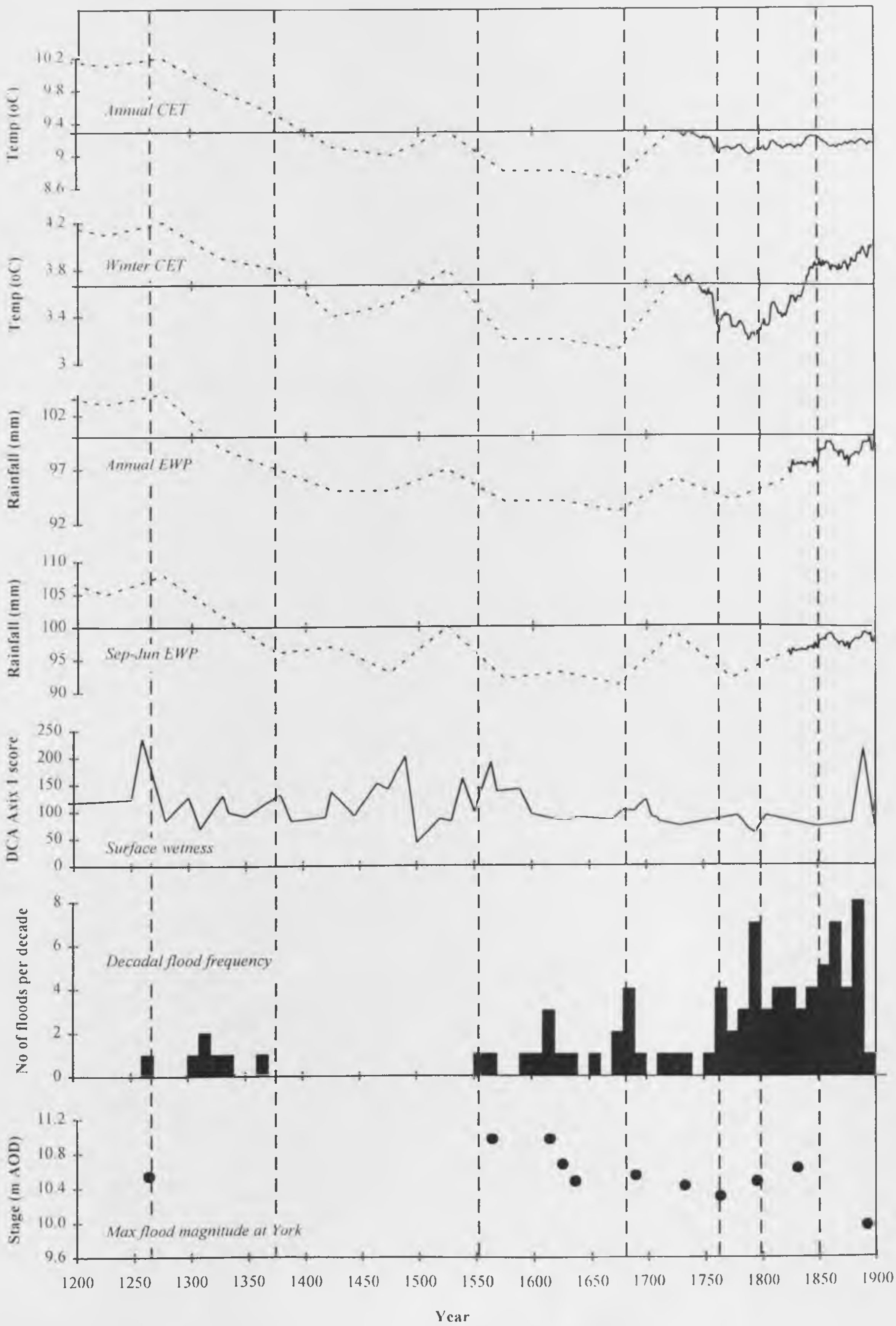
(2) Floods

(i) *Decadal flood frequency* : Decadal flood frequency in the Ouse basin has been derived by amalgamating the documentary flood records from all major lowland tributaries (see appendix B). Localised upland summer floods have been excluded from this series in order to show only extensive lowland flood events.

(ii) *Flood magnitude* . The series shown plots maximum flood estimates from the documentary record at York (see section 4.3.3.1. for detailed description).

Chapter 6 showed that records of land-use change are very poor until the mid-nineteenth century, and therefore no data can be presented for the documentary period. Below is a chronology detailing the major secular trends in flooding and climate change for the documentary period based on the above data and findings in chapters 4 and 5.

***Figure** 7.1 : Summary diagram for the documentary period 1200-1900*



1263-1360

Documentary evidence suggests that there were a series of large floods during this period. These events may have been relatively localised since each flood is recorded at only one site. However, it is more likely that this reflects the paucity of documentary evidence in this early period. These floods coincide with a marked climatic transition, with climatic deterioration evident from around 1200 AD (Lamb, 1977). Temperatures were declining from the Medieval Optimum, reflected in a high winter severity index (Ogilvie and Farmer, 1997). Though rainfall totals also appeared to be declining in this period, some notable precipitation extremes were recorded. There was a run of extremely wet summers and mostly wet autumns and springs between 1313 and 1317, with the 1360s being a particularly wet decade (Lamb, 1977, 1982). The raised mire sequence at Bolton Fell Moss indicated a shift to increased surface wetness in this period (Barber *et al.*, 1994), probably as a consequence of declining temperatures and reduced rates of evapotranspiration. An increase in storminess also occurred in this period resulting in severe flooding along North Sea coasts as a result of rising sea level (Lamb, 1977, 1982). In summary, this period was characterised by increased flooding associated with marked climatic deterioration and increased surface wetness.

1361-1549

Notwithstanding the paucity of documentary evidence prior to the eighteenth century (Archer, 1987; Rumsby, 1991), no floods were recorded in this period, suggesting a reduced frequency of severe noteworthy floods. This coincided with a marked decline in the winter severity index (Ogilvie and Farmer, 1997) and a shift to generally milder conditions, though temperatures declined in the early part of this period (Lamb, 1982). There was also evidence of a short-lived warm phase in the early sixteenth century, attributed to an increased frequency of anticyclonic weather systems (Lamb, 1982). Proxy climate evidence at Bolton Fell Moss suggests this warm phase may have occurred slightly earlier. In general, however, surface wetness declined from the beginning of this period until the end of the sixteenth century when there was a dramatic increase in surface wetness.

1550-1680

This period was characterised by an increased frequency of very high magnitude floods. Events such as those recorded in March 1615 and September 1673 were basin-wide floods which caused widespread damage and disruption. Evidence from the Ouse at York suggests that the magnitude of these and other floods in 1564, 1625 and 1636 was extremely high, some with no modern or historical equivalent. Many of these floods were generated by snowmelt, or rain-on-snow events, and coincide with the major Europe-wide cooling associated with the Little Ice Age. Temperatures were extremely low, though marked seasonal variations were evident. 50-year average rainfall totals suggest that rainfall was also low in this period, although a shift towards increased surface wetness in evident, particularly after 1600. Large-scale upper atmospheric circulations have been inferred from proxy temperature and precipitation records (Lamb, 1977; 1982) and suggest that a reduced equator-pole temperature gradient caused northern Hemisphere climate zones to be shifted southwards. This caused more frequent blocking and meridionality in middle latitudes, and a southward displacement of prevailing depression tracks, often resulting in snowy cold weather in the British Isles (Lamb, 1977). It has been suggested by Rumsby and Macklin (1996) that the Little Ice Age was a period of low rates of fluvial activity due to reduced flood frequency and magnitude, although it appears that in the Ouse basin, wet antecedent conditions, associated with cool temperatures and low rates of evapotranspiration combined with more frequent snowfall, may have resulted in an increase in the frequency of high magnitude floods.

1681-1763

The late-seventeenth to mid-eighteenth century was characterised by an increased frequency in the incidence of localised summer flooding, and a reduced incidence in widespread lowland flooding. The majority of floods in this period were caused by thunderstorms and cloudbursts between May and August. Temperature and rainfall totals were increasing from the lows of the Little Ice Age until around 1725 when both slightly declined. Indeed, the early part of the eighteenth century is generally regarded as a warmer phase of the Little Ice Age with above average temperatures in summer. These elevated summer temperatures may have caused an increase in high intensity, short-duration convective summer storms and associated flooding.

1764-1799

The number of floods recorded in documentary sources increased markedly in this period, probably as a consequence of increasing population and improved and more frequent chronicling of events. In general this period was characterised by high flood frequency and magnitude, particularly in the 1760s. There followed a relative decline in flood frequency in the 1770s and 1780s and an increase in the 1790s. A run of severe winters occurred in the 1760s and marked the onset of a deterioration in climate which lasted until the end of the century (Lamb, 1977). Extremes of precipitation were also common in this period, with both wet and dry events (Wigley *et al.*, 1984), and surface wetness was very low. In terms of atmospheric circulations, Kington (1976) suggests that meridional circulation patterns were particularly frequent and strong in the late-eighteenth century over the British Isles, coinciding with a 22% reduction in the strength of zonal circulations occurring in mid-winter.

1800-1849

This period was characterised by moderate flood frequencies, and magnitude records at York show that only one large magnitude event occurred (1831). Annual temperatures remained relatively stable, whilst winter temperatures increased. Rainfall records indicate that totals were increasing throughout this period, and the raised mire sequence at Bolton Fell Moss suggests that surface wetness was high. No major land-use changes are recorded in this period.

1850-1899

Documentary and gauged records (see figures 7.2 and 7.3) suggest that this was a period of high flood frequency, most notably in the 1870s and early-1880s. Flood magnitudes were also high, particularly on the Don at Doncaster and the Calder at Broadreach. This coincided with high rainfall totals in the 1870s and 1880s and increasing winter temperatures. Cyclonic circulations were the dominant flood generator on both the Ouse (Cyclonic 0.45 events per year, westerly 0.41 events per year 1878-1899) and the Don (Cyclonic 0.6 events per year, westerly 0.2 events per year 1868-1899). With respect to land-use change, the 1850s until the mid-1870s represent the ‘high farming’ era, which experienced an increase in arable crops and a major expansion in field underdrainage. The last quarter of the nineteenth century represents a period of agricultural depression, when many arable areas reverted back to grassland and there was a marked reduction in land drainage schemes.

Figures 7.2 and 7.3 summarise information relating to the gauged (1863-1996) period. Two diagrams are presented to highlight the different hydrological response between northern (Swale, Ure, Nidd, Wharfe, Ouse and Derwent) and southern (Aire, Calder and Don) Yorkshire rivers The data presented are based on the following information and general findings outlined in chapters 4, 5 and 6.

(1) Climate

(i) *Temperature* : Annual average and 5-year moving average temperatures have been plotted for York (obtained from annual reports of the Yorkshire Philosophical Society) and Central England (CET - obtained from the Climatic Research Unit at the University of East Anglia).

(ii) *Rainfall* : Annual and 5-year moving average rainfall totals are plotted for York (obtained from annual reports of the Yorkshire Philosophical Society) and England and Wales (EWP - obtained from the Climatic Research Unit at the University of East Anglia). The annual frequency of POT rainfall events at Blackmoorfoot is also presented.

(iii) *Dominant flood generating atmospheric circulation* : The circulation type that generated the majority of POT floods in each hydrological sub-period has been calculated for the Ouse and Don.

(2) Floods

(i) Figure 7.2 shows the gauged flood history of the Ouse at York and is considered to be representative of northern rivers. Three flood series are presented (1) annual maximum flood (2) Floods over Q_{10} and Q_{20} thresholds (3) Annual flood frequency.

Figure 7.3 shows annual maximum series for the Don at Doncaster and the Calder at Broadreach. Annual flood frequency on the Don, and floods over Q_{10} and Q_{20} thresholds are also plotted.

(3) Land-use

Major land-use changes have been graphically summarised from chapter 6 and represent the principal variations in both northern and southern rivers. The following land-use factors are considered.

(a) Moorland gripping
(b) Rates of underdrainage
(c) The timing of increasing winter wheat
(d) The rapid increase in sheep numbers
(e) Agricultural trends
(f) Channel improvements

1900-1915

Flood frequencies and magnitudes declined markedly in this period on both northern and southern rivers. No floods $>Q_2$ were recorded on any river, and lowest 5-year average AM levels were evident on the Ouse at York and the Aire and Calder at Castleford between 1902 and 1906. Flood frequencies were also extremely low on the Ouse at York, with three consecutive 5-year period averages showing the lowest recorded flood frequencies (0.8 events per year) between 1897 and 1911. Furthermore, on the Don at Doncaster two of the lowest 5-year average flood frequencies also occurred in this period.

Temperatures were generally warmer than those of the late-nineteenth century, whilst both annual rainfall and the frequency of heavy daily rainfalls were relatively low. Westerly circulations were the dominant flood generator on the Ouse (0.31 events per year) followed by cyclonic type (0.25 events per year). However on the Don, the cyclonic type dominated flood generation (0.5 events per year).

Few significant land-use changes are evident in this period. Drainage activity was very low, associated with a generally stable period in the agricultural economy. Though with the onset of World War One, there was a reversion of grassland to arable land.

1916-1943

Significant variations in flood magnitude are evident between sites in this period. Flood magnitude generally increased from the record lows of the previous period on the Ouse at York and on the Aire and Calder at Castleford. However, on the Don at Doncaster there were a series of large floods, whilst on the Calder at Broadreach flood magnitudes generally declined. Flood frequencies remained low over this period.

In terms of climate, annual temperatures increased throughout this period, and annual rainfall totals were high, particularly in the late-1920s to early-1930s, and towards the end of this period. Westerly circulations continued to dominate flood generation on the Ouse (0.54 events per year), whilst cyclonic type generated the majority of floods on the Don (0.53 events per year).

However, it is more likely that land-use changes caused the inter-site variations in flood magnitude. Most significantly perhaps, is the inauguration of the River Ouse (Yorkshire) Catchment Board in the early-1930s, which marks the onset of increased and sustained channel modification. The majority of schemes were carried out on the southern industrial and heavily populated rivers of the Aire, Calder and Don, and it is these rivers that show the most marked variations in magnitude during, and after this period. On the Don at Doncaster for example, the series of large floods observed in this period may appear disproportionately large in an historical context, since large-scale channel improvements after this time have significantly reduced flood flows in this area. Similarly, the continued decline in flood magnitudes of the Calder is probably a response to channel alterations. In contrast, the Ouse at York and upstream tributaries were relatively unmanaged at this time, and probably represent a more natural response to climatic factors, particularly since drainage activity was very low due to economic depression, until the introduction of grant-aid in 1939.

1944-1968

The 1940s marks the onset of very significant changes in land-use, climate and flood regime. On the Ouse at York there was a marked and sustained increase in flood frequency. There is also some evidence of this increase on the Nidd and Wharfe, although records are too short to draw firm conclusions. There appears to have been large inter-annual variations in flood frequency on the Ouse, Nidd and Wharfe in the 1950s, followed by high flood frequency in the mid-1960s. Furthermore, there was a cluster of spring POT floods in the late-1940s and the mid-to-late 1960s. Flood magnitudes were more variable over this period, northern rivers show that peaks occurred in the mid-to-late 1940s and the mid-to-late 1960s. However, northern and southern rivers show significant variations in magnitude. On the River Calder at Broadreach and the Don at Doncaster, flood magnitudes declined throughout this period. On the Aire and Calder at Castleford, whilst the peaks and troughs in magnitude appear to coincide with northern rivers, the scale of this variation differs, with much less variation evident

Flood magnitude records on the northern rivers appear to track peaks and troughs in rainfall series, particularly in the mid-late 1940s and the 1960s. Peaks in heavy daily rainfall also tend to coincide with peaks in flood frequency and magnitude. Westerly atmospheric circulations generated the majority of floods in the north, generating 1.1 events per year on the Ouse at York, followed by cyclonics which generated 0.9 events per year. On the southern rivers cyclonic circulations were the dominant flood generator (0.8 events per year on the Don), followed by westerly circulations (0.2 events per year on the Don). The annual frequency of westerly circulations has declined markedly since the 1950s (Briffa *et al.*, 1990; Jones and Kelly, 1982), and this is reflected by a reduced number of floods generated by westerly circulations, particularly in the later part of this period. However, there appear to be no clear climatic explanation for the large increase in flood frequency at York, which may relate to a series of large-scale land-use changes.

With respect to the northern rivers increasing grant-aid resulted in a major expansion of moorland gripping in the Yorkshire Dales, which continued throughout this period. There was also an increase in lowland underdrainage after 1939, associated with a massive plough-up campaign which converted large areas of grassland in to arable land, to meet demand for increased home food production during the Second World War. This may have resulted in more rapid runoff from the uplands and slower runoff from the lowlands combining flood peaks downstream. Effects such as these are likely to be greatest for small and moderate floods (Higgs, 1987a) and may explain the increase in frequency of events of this magnitude. Variations in flood magnitude between northern and southern tributaries may be explained by increasing channel improvement and modification schemes in the southern rivers which would have reduced local flood peaks.

1969-1977

Flood frequencies and magnitudes were extremely low between 1969 and 1977. Six of eight POT records showed that the lowest 5-year average flood frequencies occurred between 1972 and 1976. Similarly five of the eight AM records showed that the lowest 5-year average magnitudes were also recorded between 1972 and 1976. These low flood frequencies and magnitudes coincides with a well documented period of low rainfall, evident in annual, seasonal and POT rainfall series. Whilst flood frequencies were low, those floods that did occur were predominantly generated by cyclonic circulations No major land-use changes were initiated in this period.

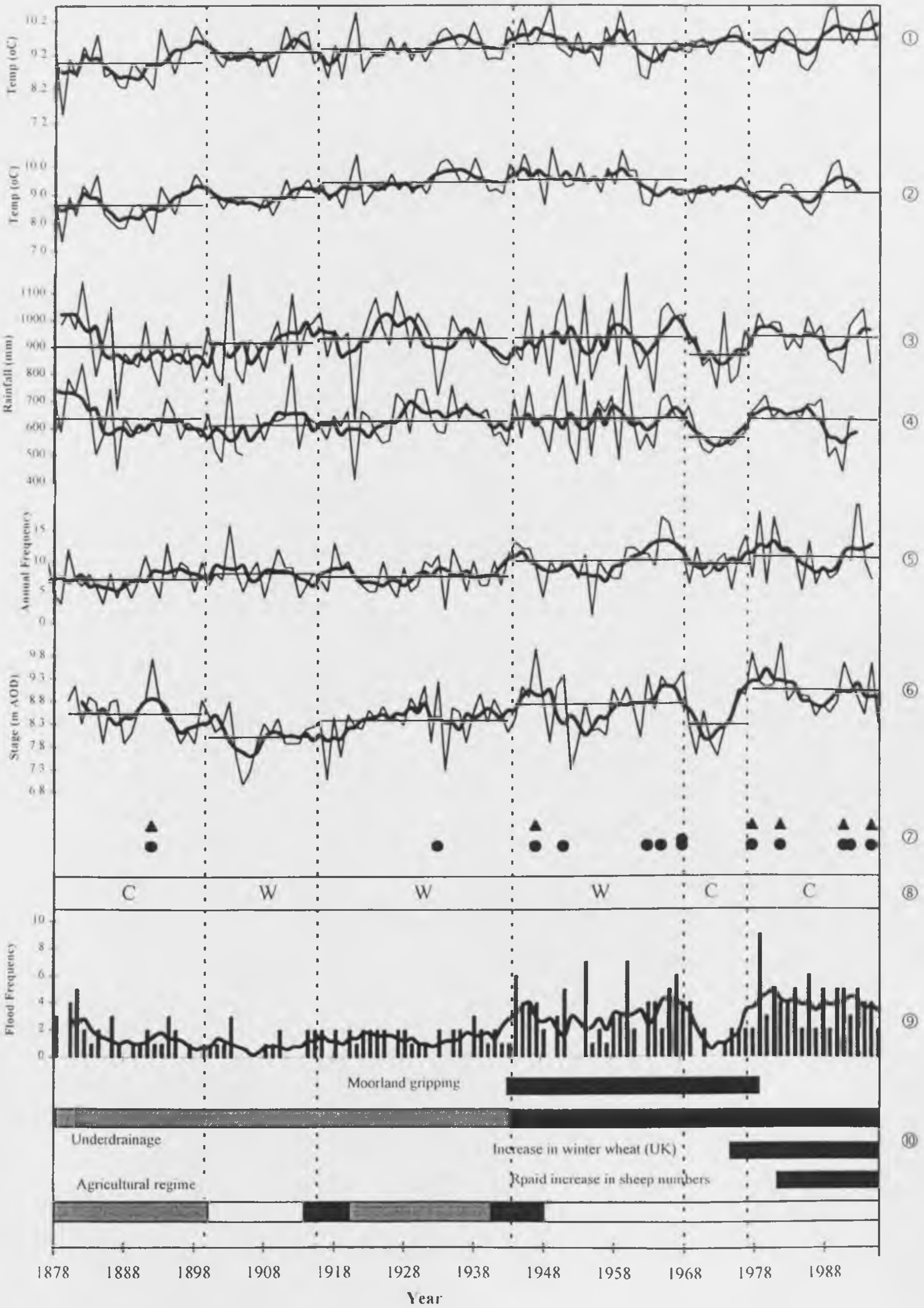
1978-1996

All rivers in the Yorkshire Ouse basin showed a dramatic increase in flood frequency and magnitude during this period. Flood frequencies peaked in the early 1980s and declined slightly in the late 1980s and 1990s, though still relatively high in an historical context. In the 10-year period between 1977 and 1986 all eight POT records experienced the highest 5-year average flood frequencies Flood magnitudes peaked in the late-1970s to early 1980s, followed by a decline in the mid 1980s, and an increase in the 1990s. Furthermore, five AM records showed the highest 5-year averages in this period, particularly between 1992 and 1996 on northern rivers. Large magnitude floods have been particularly frequent in this period, at York for example, four out of the six floods exceeding Q_{20} in the 119-year record have occurred since 1977 (i.e. 1978, 1982, 1991 and 1995). Similarly, these large floods have been registered on all other northern rivers, however, the magnitudes recorded on the River Ure were exceptional. In contrast, flood magnitudes have been lower on the southern rivers, with most events not exceeding the Q_{10} threshold, probably as a consequence of earlier channel improvement and flood defences.

This period has also experienced an increase in the frequency of spring flood events, associated with an increase in spring rainfall. In general, annual, seasonal and POT rainfall records peaked around the mid-1980s, in-phase with flood record peaks. More significantly, the increase in flood frequency and magnitude in this period has been associated with an increase in the incidence of floods generated by cyclonic circulations, as a consequence of an increase in the frequency of cyclonic days per year in the Lamb catalogue. The number of floods per year generated by cyclonic circulations was 1.3 and 1.5 on the Ouse and Don respectively, by far the highest frequencies in the instrumental period. The number of floods generated by south-westerly circulations has also increased markedly, particularly on the Ouse at York associated with an increase in the frequency of south-westerly days.

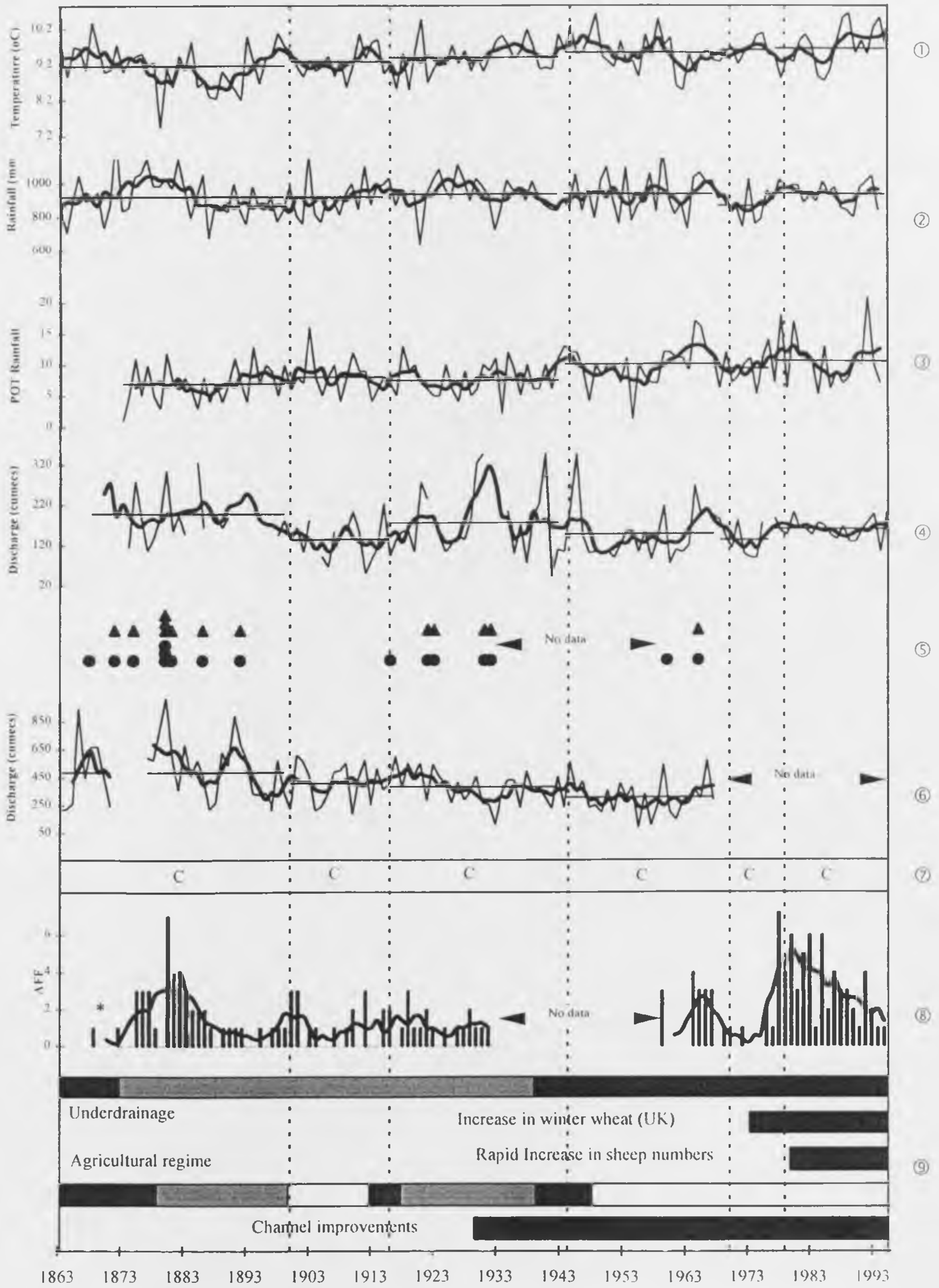
Land-use changes which may have exacerbated these increases in flood frequency and magnitude include the cumulative effects of moorland gripping, since the continued erosion of ‘grips’ has resulted in a dense network of deep artificial channels in some areas of the Dales, that undoubtedly speed runoff from the uplands. Furthermore, increasing cultivation of ‘winter wheat’, and increasing sheep numbers in the Yorkshire Dales may also have promoted more rapid runoff from agricultural land.

Figure 7.2 : Summary diagram for northern Yorkshire rivers 1878-1996



①Annual CET. ② Annual temperature at York. ③ Annual EWP. ④Annual rainfall at York
⑤Annual frequency of POT rainfall at Blackmoorfoot. ⑥ Flood stage at York. All line diagrams show raw data, 5-year moving average and period means. ⑦Q_{10} (filled circle) and Q_{20} (filled triangle) POT floods at York
⑧Dominant flood generating circulation type (W - Westerly, C - Cyclonic)
⑨Annual flood frequency at York (with 5-yr moving average). ⑩Land-use changes : showing (i) main phase of moorland gripping (ii) Underdrainage : low rates (grey area) and high rates (black area). (iii) increase in winter wheat
(iv) Increasing sheep numbers in the Yorkshire Dales. (v) Agricultural trends : showing periods of depression (grey areas), stability (white areas), and reversions of grassland to arable land (black areas)

Figure 7.3 : Summary diagram for southern Yorkshire rivers 1863-1996



① Annual CET. ② Annual EWP. ③ Annual frequency of POT rainfall at Blackmoorfoot

④AM series - Don at Doncaster. ⑤ Q10 (circle) and Q20 (triangle) POT floods at Doncaster.

⑥AM series - Calder at Broardreach. ⑦ Dominant flood generating circulation typr (Don) (C - cyclonic)

⑧Annual flood frequency - Don at Doncaster.

⑨Land-use changes : (I)Rates of underdrainage : low rates (grey area) and high rates (black area)

(ii) increase in winter wheat. (iii) Increasing sheep numbers in the Yorkshire Dales.

(iv) Agricultural trends : showing periods of depression (grey area), stability (white area) and reversions of grassland to arable land (black areas).

Summary

A series of large floods were documented between 1263 and 1360, associated with a marked climatic deterioration. Temperatures were declining from the Medieval Optimum, and a run of severe winters and extremes of precipitation resulted in increased surface wetness. The severity of winters declined and there was a shift to generally milder conditions between 1361 and 1549 when no documentary floods were recorded. This warmer phase was attributed to an increase in the frequency of anticyclonic weather systems. In contrast the period between 1550 and 1680 experienced an extremely high frequency of large magnitude floods. This period coincides with the onset of the Little Ice Age, characterised by very low temperatures, increasing surface wetness, more frequent and severe snowfalls, and seasonal extremes of temperature and rainfall. This climatic deterioration resulted in a southward shift of prevailing depression tracks and an increase in blocking and meridionality in middle latitudes. However, during a warmer phase of the Little Ice Age there appears to have been an increase in the frequency of localised summer flooding between 1681 and 1763. During this period summer temperatures were above average and may have resulted in more frequent high intensity, short duration convective storms. Extensive lowland flooding again increased between 1764 and 1799, particularly in the 1760s and 1790s, associated with severe winters, heavy rainfall and an increase in the frequency of meridional circulations in the late eighteenth century. This was followed by a period of fairly moderate flood frequency and magnitude between 1800 and 1849 when annual rainfall was increasing and surface wetness was high. The period 1850-1899 was characterised by high flood frequency and magnitude, particularly in the 1870s and early-1880s, coinciding with high rainfall totals and a high incidence of cyclonic flood generation. A phase of intense underdrainage activity also occurred in the early part of this period, followed by a relative decline in the last quarter of the century.

Gauged flood records indicate that the period between 1900 and 1916 was characterised by very low flood frequency and magnitude, associated with low rainfall, warmer temperatures and an increase in westerly flood generation on northern rivers. Drainage activity was relatively low during this period as a result of a stable agricultural economy. The period 1916 to 1943 was characterised by marked variations in flood magnitude between northern and southern rivers. While magnitude generally increased on the northern rivers, magnitude declined on some of the southern rivers as a result of channel improvement and flood defence works. Flood frequency remained relatively low over this period. Around 1944 there was a marked and sustained increase in flood frequency on the northern rivers. This was associated with an increase in the incidence of heavy daily rainfalls, greater westerly flood generation and major land-use changes. The number of moorland gripping and underdrainage schemes accelerated dramatically in response to the introduction of government grant-aid. Furthermore, a massive plough-up campaign resulted in large areas of grassland being converted to arable land. These changes may have caused increased rates of runoff from the uplands and slowed runoff from the lowlands, resulting in greater flood peaks in the lowland areas. Further variations in flood magnitude between northern and southern rivers was again evident in this period, as a result of continued intense channel management on the southern rivers systems. Between 1969 and 1977 both flood frequency and flood magnitude declined to very low levels, principally due to reduced rainfall. In contrast, the most recent period between 1978 and 1996 has experienced some of the highest flood frequencies and magnitudes on record, with new maximum peak discharges recorded on many rivers. This increase has been associated with increasing rainfall and more significantly, increases in the frequency of floods generated under cyclonic and south-westerly circulations, combined with an increase in annual frequencies of these circulation types. A number of land-use changes have also occurred in this period which are likely to have promoted more rapid runoff from agricultural land. First, there has been an increase in the area of crops under winter-sown regimes, and second there has been a dramatic increase in sheep numbers, both of which have been shown to increase runoff. Furthermore, the cumulative effects of moorland gripping and the continued erosion of these channels has further increased runoff from the upland areas.

There are a number of similarities and differences between variations in flood frequency and magnitude on the Ouse and other British flood series. For example, a high frequency of large floods has been documented on the Rivers Dee, Tyne and Ouse in the late eighteenth century. Similarly, between the 1870s and 1890s a number of large events have been recorded on the Dee, Tweed, Tyne, Severn and Ouse. Low flood frequency during the first two decades of the twentieth century on the Tyne is also mirrored by Ouse basin records. However, many rivers in the UK experienced an increase in flood frequency in the 1920s, whereas the major increase in flood frequency on the Ouse is dated to the 1940s, associated with increasing heavy daily rainfalls and agricultural land-use changes. Very low flood frequencies and magnitudes in the late-1960s and 1970s have been recorded throughout the UK, including the Ouse. Furthermore, the extremely high flood frequencies and magnitudes experienced since the early-1980s is also a feature common to most UK flood records. These nation-wide, synchronous variations in flood frequency and magnitude suggest that short-term climate change is the primary driving mechanism explaining variations in flood records (hemispheric-scale atmospheric circulations and linkages to UK flooding are examined in the next section). However, the effects of land-use changes can further 'sensitise' catchments to climate changes (Macklin *et al.*, 1992a). In the Ouse basin for example, it appears that a combination of a shift in climate in the last two decades which has increased the frequency and cyclonic and south-westerly atmospheric circulations, and major large-scale land-use changes have resulted in some of the highest flood frequencies and magnitudes on record. Although, it appears that major channel modifications, particularly for flood defence purposes can significantly alter natural flood response. There is evidence of this on the River Thames since the 1940s and on the southern Ouse basin rivers since the 1930s.

7.2 HEMISPHERIC-SCALE ATMOSPHERIC CIRCULATIONS AND FLOODING

One of the key research aims of this project was to examine to role of atmospheric circulations in flood generation (reviewed in section 2.3.3.). Rumsby and Macklin (1994) studied large-scale circulation types and flood response in the Tyne basin, northern England. Specific hemispheric-scale configurations of the upper atmosphere were found to relate to variations in flood frequency and magnitude. Major floods (>20 year return period) were found to occur more frequently in periods with an enhanced meridional (north/south) circulation, whereas more moderate floods (5-20 year return period) were found to occur more frequently under an enhanced zonal (west to east) circulation regime. These authors used annual frequencies of circulation types from the Lamb catalogue to classify periods as being enhanced zonal, meridional or intermediate (no dominant regime). This study has investigated flood generation on an event basis, and therefore allows for more detailed examination and re-evaluation of flood and circulation relationships.

Zonal circulation types in the Lamb catalogue are westerly, south-westerly and north-westerly, and their anticyclonic and cyclonic hybrids. Meridional circulation types in the Lamb catalogue are northerly, southerly, easterly, north-easterly and south-easterly, and their anticyclonic and cyclonic hybrids.

To investigate which individual meridional and zonal circulation types generate floods in the Ouse basin we can examine the results of the flood generating circulation study undertaken in chapter 5, which classified 1340 POT flood events as being generated by one individual circulation type. Tables 7.2 & 7.3 show the number of POT floods in the Ouse basin generated by meridional and zonal circulation types. This illustrates that meridional circulation types generated relatively few floods, only 12.76 %, whilst zonal types generated 46.87% of all POT events. Zonal and meridional types combined generated 59.63% of all POT flood events, however the classification outlined by Rumsby and Macklin (1994) does not include pure cyclonic circulations. This one type alone generated 502 POT floods (37.46%) in the Ouse basin The importance of cyclonic circulations is emphasised further with respect to flood magnitude. Table 7.4 shows the number of POT floods generated by zonal and meridional types and the individual cyclonic category for the flood magnitude ranges defined in section 5.4.3.2 Meriodional types generate far fewer floods than zonal or pure cyclonic circulation Whilst the percentage of floods generated by meridional types increases with magnitude, this type only accounts for one quarter of POT floods over the Q_{10} threshold At the highest magnitudes, cyclonic circulations generate the majority of flood events. These findings indicate that the zonal and meridional classification suggested by Rumsby and Macklin (1994) does not take account of one of the most important flood generating circulations in the Ouse basin (i.e. cyclonic).

However, figure 7.4, which shows AM and AFF, and floods greater than Q_{10} and Q_{20} at York, suggests that meridional periods are indeed characterised by high flood frequency and magnitude as suggested by Rumsby and Macklin (1994). Furthermore, zonal periods tend to show more moderate magnitudes and frequencies, whilst intermediate periods are characterised by very low flood frequencies and magnitudes. Given the fact that meridional circulations types generate relatively few large flood events, an alternative explanation must be sought as to why these periods tend to experience high flood frequency and magnitude. The answer to this question undoubtedly requires further detailed investigation, however a tentative hypothesis can be suggested. During periods of enhanced meridional circulation the frequency of zonal weather types is relatively low. Westerly circulations are the dominant zonal type and have been shown to be important in flood generation in the Ouse basin. However, when the frequency of westerly circulations declines, this is often associated with an increase in cyclonic circulations (P.D. Jones pers. comm.). Therefore, it may be that increased flood frequencies and magnitudes experienced during meridional periods is a result of increasing cyclonic activity, combined with generally wetter antecedent catchment conditions as a result of lower temperatures and increase wetness often experienced in meridional periods. The importance of cyclonic circulations is further emphasised by the most recent period, characterised by an increase in anticyclonic and cyclonic circulation types, which has experienced the highest flood frequencies and magnitudes on record. Clearly, this is an area worthy of more detailed and robust investigation since it does appear that hemispheric-scale variations in atmospheric circulation coincide with changes in flood regime.

Table 7.2 : Number of POT floods in the Ouse basin generated by ***zonal*** *circulation types.*

Circulation type	No of POT flood generated	% of zonal floods
Anticyclonic-south-westerly (ASW)	0	0
Anticyclonic-westerly (AW)	9	1.43
Anticyclonic-north-westerly (ANW)	0	0
South-westerly (SW)	65	10.35
Westerly (W)	383	60.99
North-westerly (NW)	24	3.82
Cyclonic-south-westerly (CSW)	24	3.82
Cyclonic-westerly (CW)	113	18.00
Cyclonic-north-westerly (CNW)	10	1.59
Total number of zonal POT floods	**628**	

Table 7.3 : Number of POT floods in the Ouse basin generated by ***meridional*** *circulation types*

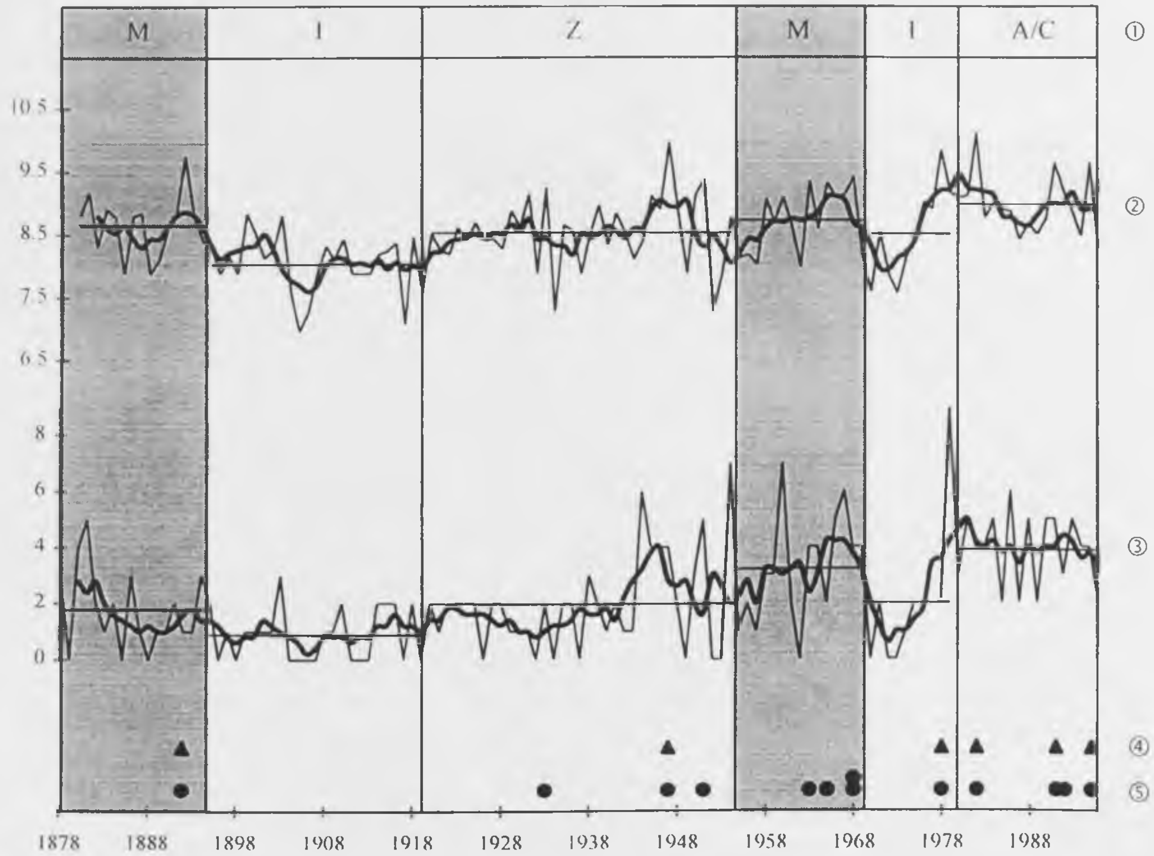
Circulation type	No of POT flood generated	% of meridional floods
Anticyclonic-north-easterly (ANE)	1	0.58
Anticyclonic-easterly (AE)	0	0
Anticyclonic-south-easterly (ASE)	0	0
Anticyclonic-southerly (AS)	0	0
Anticyclonic-northerly (AN)	0	0
North-easterly (NE)	6	3.51
Easterly (E)	16	9.63
South-easterly (SE)	11	6.43
Southerly (S)	47	27.49
Northerly (N)	12	7.02
Cyclonic-north-easterly (CNE)	5	2.92
Cyclonic-easterly (CE)	22	13.67
Cyclonic-south-easterly (CSE)	3	1.75
Cyclonic-southerly (CS)	13	7.60
Cyclonic-northerly (CN)	35	20.47
Total number of meridional POT floods	**171**	

Table 7.4 : The magnitude of POT floods generated by meridional, zonal and cyclonic circulations

Flood Magnitude	Meridional		Zonal		Cyclonic (C)	
	No.	*%*	*No.*	*%*	*No.*	*%*
Minor(standard threshold $< Q_2$*)*	136	13.93	522	49.62	394	37.45
Moderate ($>= Q_2 < Q_{10}$*)*	27	13.57	86	43.22	86	43.22
Major ($>= Q_{10}$*)*	14	25.00	20	35.71	22	39.29

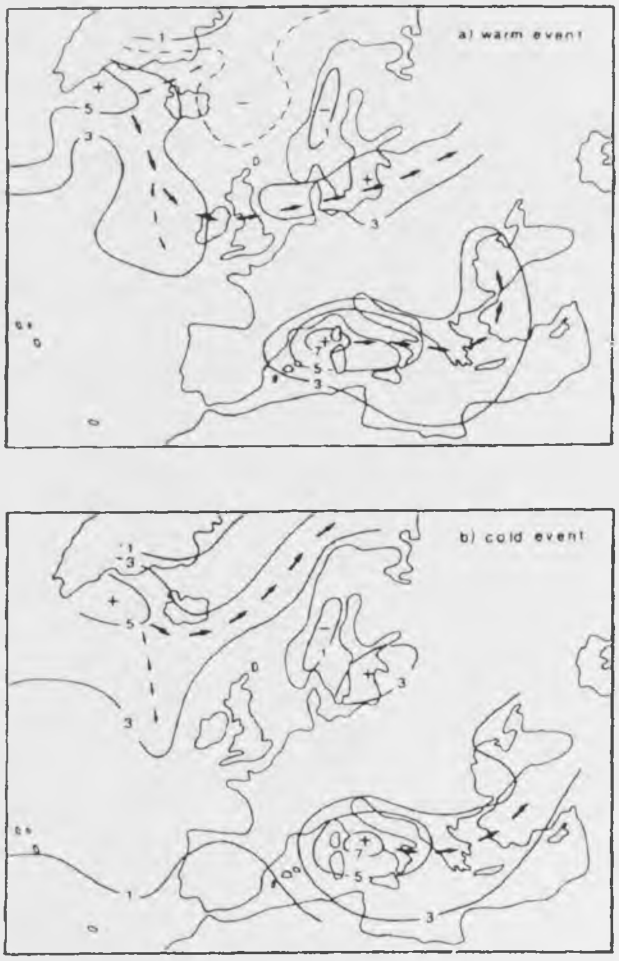
Global-scale climate phenomena have also been shown to impact on atmospheric circulation in the northern hemisphere mid-latitudes. Teleconections between El Niño-Southern Oscillation (ENSO) 'warm' and 'cold' events, and atmospheric circulation in Europe (Fraedrich, 1990; Fraedrich and Muller, 1992) and British Isles (Wilby, 1993) have been proposed. Over Europe, the European Grosswetter daily classification of circulation types was used to examine the response of winter atmospheric circulation to warm (26 events) and cold (22 events) ENSO extremes between 1880 and 1989 (Fraedrich and Müller, 1992). It was found that in the winter months following an ENSO warm event that on average precipitation declined in Scandinavia, but increased in western, south-western and central Europe. This was attributed to a shift in the position of the mean cyclone track (see figure 7.5) over the British Isles and central Europe. In general, warm ENSO events tend to produce more cyclonic Grosswetter situations over western and central Europe than cold ENSO events, which tend to shift the mean cyclone track north, over Scandinavia, increasing precipitation in this region. Similar results were obtained by Wilby (1993) who used the Lamb catalogue to examine the effects of ENSO extremes on UK circulation types, and found that on average, cyclonic type tended to occur more frequently during the winter of a warm ENSO event. Given the relationship between cyclonic circulations and flooding highlighted in this thesis, this may influence flood response in the Ouse basin, and other parts of the UK, and is again highlighted as an area of future research in terms of the large-scale climatic controls of flooding in the UK.

Figure 7.4 : *Flood frequency and magnitude at York during meridional, zonal and intermediate periods*



① Climate regime as defined by Rumsby and Macklin (1994)
M = meridional, Z = zonal, I = intermediate, A/C = increased anticyclonics and cyclonics
② Annual maximum flood on the Ouse at York 1880-1996
③ Annual flood frequency on the Ouse at York 1878-1996
④ Floods $>Q_{10}$ on the Ouse at York
⑤Floods $>Q_{20}$ on the Ouse at York

***Figure** 7.5 : Number of the daily occurrence of cyclones in 5° latitude by 5° longitude grid cells during an ensemble-averaged warm ENSO and cold ENSO event in winter, each comprised of eight episodes (1952-1989). (From Fraedrich and Müller, 1992)*



CHAPTER 8

CONCLUSIONS

The principal research aim of this study has been to investigate variations in flood frequency and magnitude in the Yorkshire Ouse basin, and to examine the causes of these variations with respect to climate and land-use change. Documentary flood records dating to the eleventh century and a number of exceptionally long gauged flood records in the Ouse basin represent a previously unexplored source of flood data with which to examine linkages between long-term flood response and climate and land-use changes. This concluding chapter outlines the main findings of this research and makes a number of recommendations for future study.

1. Historic variations in flood frequency and magnitude in the Ouse basin

A number of large floods were recorded between 1263 and 1360, followed by a prolonged period of low flood frequency and magnitude between 1361 and 1549 when no floods were documented. Some of the highest magnitude flood events on record were documented between 1550 and 1681, whereas more moderate magnitude, localised summer floods became more prevalent between 1681 and 1763. High flood frequencies and magnitudes were evident between 1734 and 1799, and 1850 to 1899, with the intervening period experiencing fairly moderate flood frequencies and magnitudes. The early twentieth century was characterised by extremely low flood frequency and magnitude, particularly between 1900 and 1915. Flood frequencies remained relatively low over the period 1916 to 1943, whereas magnitude series showed a high degree of inter-site variation. Whilst flood magnitudes generally increased at most sites throughout this period, flood records on the Calder show magnitudes to be declining, and on the River Don there was a series of very large floods towards the end of this period. Around 1944 there was a marked and sustained increase in flood frequency, particularly on the Ouse at York, until around 1968. Over this period flood magnitudes became more variable, with greater divergence between northern and southern Ouse tributaries. The northern rural rivers showed peaks in magnitude in the mid-to-late 1940s and the mid-to-late 1960s, whereas on the Calder and Don magnitudes progressively declined. The period between 1969 and 1977 experienced a shift to extremely low flood frequency and magnitude evident at all sites. This was followed by a period characterised by very high flood frequency and magnitude with record

5-year averages. Flood frequency peaked in the early 1980s and declined slightly towards the 1990s. Flood magnitudes peaked in the late 1970s to the early 1980s and again in the 1990s.

2. Climatic controls of flooding in the Ouse basin

The documentary record

Two periods of marked climatic deterioration have been associated with a series of large flood events in the Ouse basin. The first of this occurred between 1263 and 1360 when temperature was declining from the Medieval Optimum and there were increases in winter severity and storminess. This was also a period of high surface wetness and reduced rates of evapotranspiration. The second period occurred around the time of the onset of the Little Ice Age, between 1550 and 1680 Some of the largest magnitude floods ever recorded occurred during this period and were often as a result of snowmelt or rain-on-snow processes associated with lower temperatures and a southward shift in the prevailing cyclonic storm tracks.

Other periods in the documentary record were characterised by less frequent and lower magnitude flooding. Between 1361 and 1550, generally mild conditions and decreasing winter severity resulted in no floods being documented. Localised summer floods were more frequent between 1681 and 1763, during a warmer phase of the Little Ice Age when summer temperatures were above average and the frequency of convective storms increased

More detailed climate records from the mid-eighteenth century indicate that two further periods of high flood frequency and magnitude in the late-eighteenth and late-nineteenth centuries were associated with increased rainfall totals.

The gauged record

Analysis of annual, seasonal and POT rainfall series found that such data are often limited when trying to establish links with long-term flood series, since such records consider every day (i.e. annual and seasonal) or days above a specified threshold (POT), which do not specifically relate to individual flood events. Whilst some obvious linkages between rainfall and flood series are evident, such wetter periods tending to coincide with periods of high flood frequency, it became clear that studying the flood generation process on an event basis would significantly enhance understanding of flood and climate interactions.

The methodology developed to investigate synoptic flood generation using daily rainfall records and the Lamb catalogue indicated that four circulation types generated the majority of floods in the Ouse basin. cyclonic. westerly, cyclonic-westerly and south-westerly respectively. The importance of individual types can vary according to geographical location, for example, in the most easterly areas of the Ouse basin (i.e. Don and Derwent catchments) cyclonic and easterly circulations are the dominant flood generators, whilst westerly circulations are relatively unimportant. This is linked to the geographical precipitation delivery of circulation types, since westerly circulations have a west-east precipitation gradient, whereas cyclonic circulations are generally slower moving and tend to deliver a more uniform distribution of rainfall Cyclonic circulation types also generate the majority of major floods in the Ouse basin. whilst the importance of westerly circulations declines with increasing magnitude. Several periods characterised by high flood frequency and magnitude coincide with a high frequency of cyclonic days and an increase in cyclonic flood generation, particularly the mid-1870s to mid-1890s, the late-1940s and 1950s, and between the late-1970s and mid-1980s. A higher frequency of westerly generated floods was evident in the 1940s, but declined after the 1950s, as a result of a marked decline in the annual frequency of westerly circulations. Furthermore, south-westerly generated floods have increased dramatically since the late-1960s associated with increasing annual occurrence of south-westerly types In terms of seasonality, floods generated under westerly and cyclonic-westerly circulations occur most frequently in winter. Floods generated under cyclonic conditions are more evenly spread throughout the seasons, and south-westerly generated floods tend to occur most frequently in winter and autumn.

With respect to links with large-scale (hemispheric) circulation patterns, previous work has suggested that large floods tend to occur in periods with enhanced meridional (north/south) circulations. moderate floods in periods with enhanced zonal (west to east) circulation, and low magnitude floods in intermediate periods, with no dominant circulation regime. This study found that meridional circulation types generated relatively few flood events (12.8% of all POT floods), and further emphasises the importance of cyclonic circulation types which generated 37.4% of all POT floods, and was the most important type with respect to generating high magnitude floods. Zonal circulation types generated 46.9% of POT floods and were shown to be important at both moderate and major flood magnitudes.

Future climate change

The effect of future climate change on flood frequency and magnitude in the Ouse basin is difficult to assess given the uncertainties surrounding GCM predictions. Climate change scenarios for the British Isles give a general consensus that with rising temperatures precipitation will increase in winter and that this will be greatest in the north and west. The most probable effect of postulated increases in winter rainfall, storminess and flood producing rainfalls in the Ouse basin would be a continued increase in flood frequency and magnitude. However, rising temperatures, may reduce snow-cover which could have a significant effect on flood magnitude, since most of the largest historic flood events in the Yorkshire Ouse basin have been influenced by snowmelt.

Assessing the future effects of changes in the atmospheric circulation on flooding is, however, more problematic. Rumsby and Macklin (1994) suggest that an increase in global temperature would reduce the equator-pole temperature gradient and lead to an enhanced zonal circulation regime, which would in turn increase the frequency of westerly circulation types. Alternatively Sweeney and O'Hare (1992) and Jones (1992) suggest that a reduced thermal gradient would result in a continued decline in westerly circulations, which could result in a higher frequency of large flood events because of increased convective activity and more intense depressions.

3. Land-use controls of flooding in the Ouse basin

Temporal and spatial variations in four main areas of land-use change have been investigated, (1) agricultural land-use and practice (2) agricultural land drainage (3) river channelization (4) reservoir construction, and linkages to flood series suggested. Detailed records of land-use are available from around the mid-nineteenth century, therefore only the effects on the gauged flood record can be considered.

One of the most marked variations in the flood record occurred around 1944, when flood frequency dramatically increased on the Ouse at York. This rise was associated with a number of significant land-use changes. Around this time there was a large-scale expansion in land drainage associated with increased demand for home food production, and the introduction of government grant-aid towards the cost of such schemes. Widespread moorland gripping in the Yorkshire Dales is likely to have increased rates of runoff from the uplands, whereas in the lowlands, field underdrainage of the heavy clay soils in the Vale of York, and a conversion of grassland (for livestock) to arable land may have reduced runoff rates. This probably resulted in a synchronisation of peak flows from upland and lowland areas and hence to the observed rise in flood frequency. Furthermore, periods of economic depression or stability, when drainage activity is generally reduced and arable land tends to revert back to grassland, are often associated with low flood frequency and magnitude, particularly between 1900-1915 and 1969-1977.

Inter-site variations in flood magnitude can also be attributed to land-use changes. Generally declining flood magnitudes on southern industrialised rivers from the 1930s onwards appears to be associated with the establishment of Catchment Boards and initiation of channel improvement and flood defence schemes, which are likely to have reduced local flood levels. This is in direct contrast to the rural rivers in the northern part of the Ouse basin which are relatively unmanaged, where flood magnitudes generally increase from the 1930s

More recent changes in land-use which may have affected flood frequency and magnitude are the rapid increase in livestock numbers, particularly in the Yorkshire Dales, and a shift towards the cultivation of winter cereals, although these linkages are very tentative and require more detailed study. However, it appears that the threefold increase in areas of the UK under winter wheat and the large increase in sheep numbers in the Yorkshire Dales may have significantly increased runoff rates, and be partially responsible for the recent extreme flood frequency and magnitude levels.

However, in most cases variations in flood series must be interpreted by considering the interactions between climate and land-use changes. For example, the 1944 increase in flood frequency at York was associated with increases in land drainage and large-scale changes in crop production, and an increase in the incidence of heavy daily rainfall. Furthermore, the most recent period which has experienced some of the highest flood frequencies and magnitudes on record, has been associated with an increase in the frequency of cyclonic and south-westerly generated floods and increases in livestock numbers and winter cereals. In short, there are often several contributory factors forcing changes in flood regime. Undoubtedly climate is the primary driver behind these changes, but the scale and direction of flood variation can be further sensitised by variations in land-use.

4. Recommendations for future study

This study represents the first major investigation of the response of Ouse basin rivers to recent environmental change, and has consequently highlighted many areas that would benefit from more extensive investigation.

Firstly, the location of flood series examined in this study were confined to the lower reaches of major Ouse tributaries, in order to dovetail with other elements of the LOIS project. Clearly, understanding of flood response in the Ouse basin would be significantly enhanced by the incorporation of upland and piedmont areas, therefore moving towards a more complete basin-wide approach. Significantly, some research is already being carried out in upland areas of the Yorkshire Dales (e.g. Merrett and Macklin, in press) concerned with establishing the long-term flood history of this area, derived from analysis of coarse floods deposits. A future research aim therefore would be to widen the spatial-scale of study, and incorporate a variety of techniques to derive flood histories, including sedimentological, documentary and gauged evidence.

Secondly, allied with a basin-wide flood studies approach is the need to improve the temporal and spatial resolution of climate data. However, the key climatic driver governing flood response is undoubtedly atmospheric circulation. This study has highlighted the importance of specific atmospheric circulation types in flood generation, and there is considerable scope for further development in this area to improve understanding of synoptic flood generation. The methodology developed in this thesis for identifying circulation types that generate floods would benefit from the inclusion of more climatic parameters. For example, little work has been conducted relating to the synoptic cause of snowmelt floods. Temperature, rainfall and snow data (if available) could be used for this purpose to examine both snowmelt and rain-on-snow flood events. Furthermore, an index of antecedent catchment conditions could also be incorporated into this analysis to examine synoptic situations prior to floods which may promote flood generation.

This study has also highlighted that whilst there appears to be a relationship between large-scale configurations of the upper atmosphere (e.g. zonal and meridional) and flood response, this is often poorly understood and is an important area for future research. These linkages between atmospheric circulation and flooding could be investigated at a range of spatial scales, but is, however, dependent on the existence of a long daily classification. Classification schemes which could be used range from regional (e.g. the Mayes catalogue, see Mayes, 1991.), national (e.g. the Lamb catalogue), European (e.g. the European Grosswetter, see Baur, 1947.), and hemispheric-scale (e.g. Dzerdzeevskij, 1970). At the global-scale events such as ENSO extremes and their effects on flood regime in the UK may also be a profitable area of future investigation.

The third area that would benefit from more extensive investigation is that of land-use change. Major large-scale land-use changes associated with land drainage, channel modifications and agricultural land-use and practice have been shown to coincide with variations in flood series. Data relating to land-use change is often generalised and of poor spatial resolution, highlighting the need to acquire more detailed datasets, which would greatly enhance understanding of basin-scale interactions between land-use and flood hydrology. In the Ouse basin for example, more detailed information relating to the timing and extent of moorland gripping in the Yorkshire Dales could be gained from the analysis of aerial photographs. The spatial resolution of agricultural data could also be improved by collecting data at the parish rather than county level (available at the Public Record Office at Kew). Furthermore, given the importance of the recent switch to winter cereals in other parts of the UK, a survey of this practice in the Ouse basin would also be extremely useful. This thesis also showed that information relating to the timing and extent of flood embankment construction was virtually non-existent. At present this author is undertaking a survey of historical maps and aerial photographs to evaluate the utility of such a technique in established the timing of major embankment construction schemes.

In conclusion, all of the above recommendations should be considered together when examining how they affect flood response at the basin-scale. Given the problems associated with 'averaging' effects of land-use changes and the difficulty in disentangling climate and land-use driven changes in flood regime, the future emphasis of study should focus on interactions between changes in the different aspects of land-use and climate. A more complete understanding of the processes operating at the basin-scale may be aided by computer modelling of these interactions based on a high resolution spatial database.

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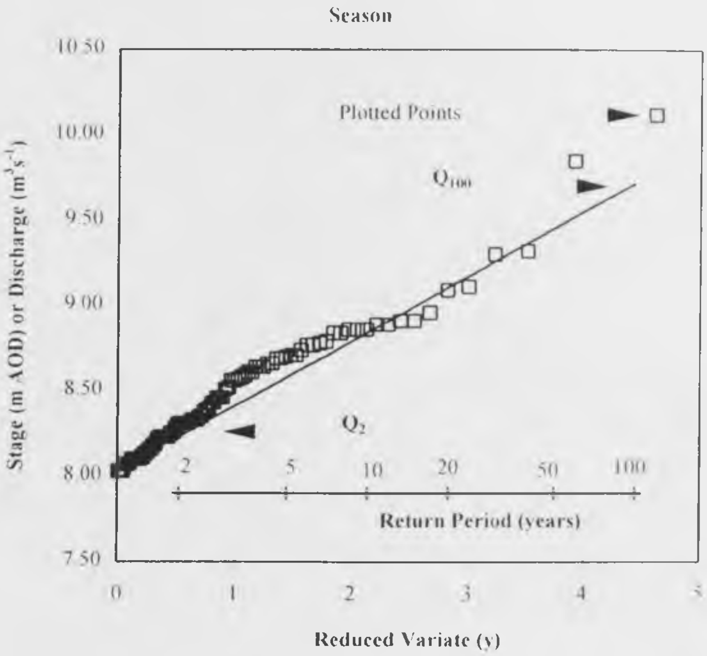
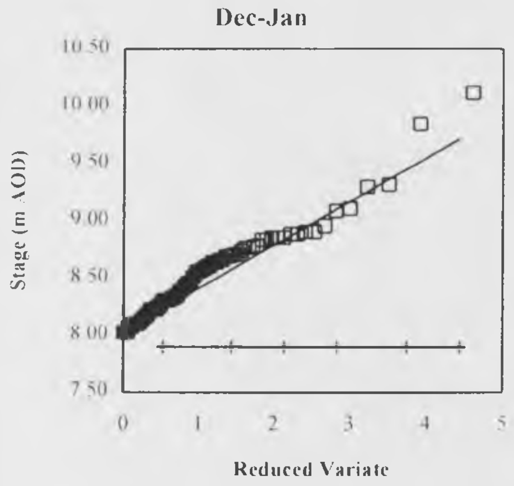
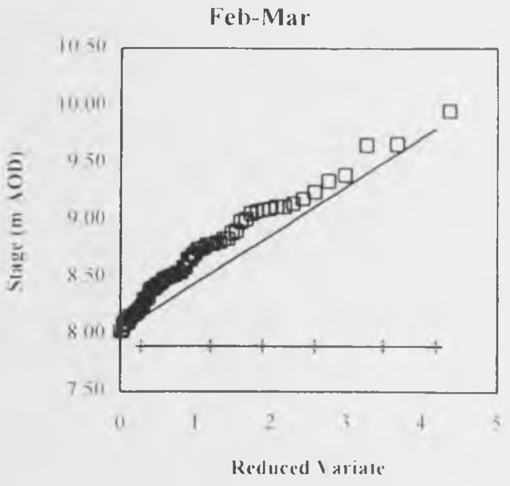
Appendix E : Yorkshire Water Services Ltd. Reservoirs in catchments

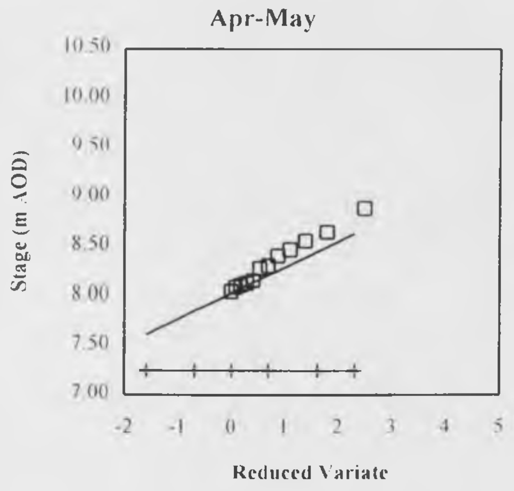
Appendix A : *Key to flood frequency distribution diagrams in Appendix A(i) - A(vii)*

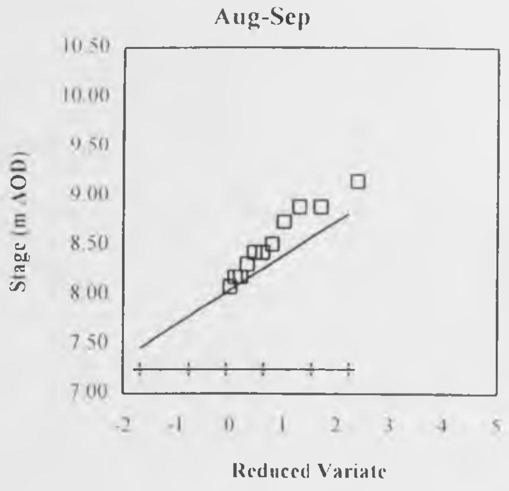


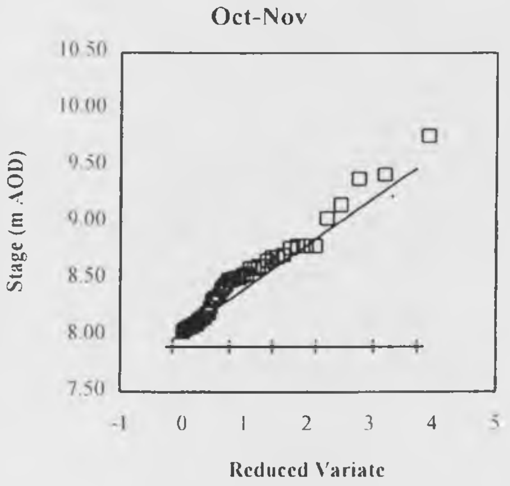
Appendix A (i) : Seasonal frequency distributions - Ouse at York 1878-1995



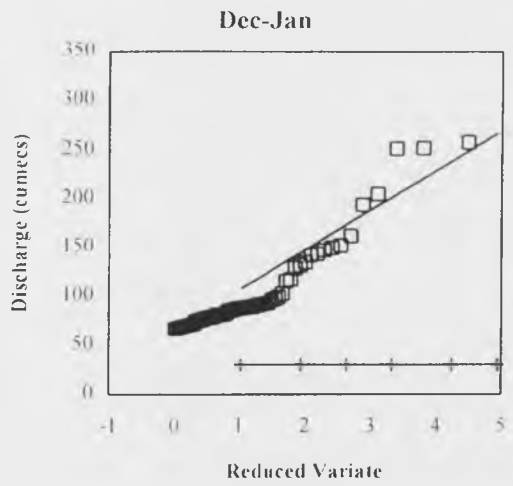


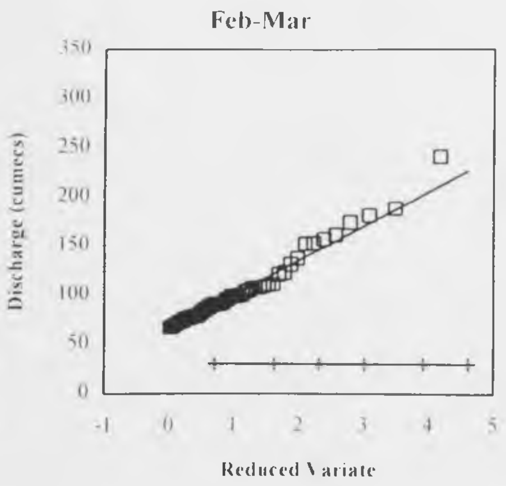


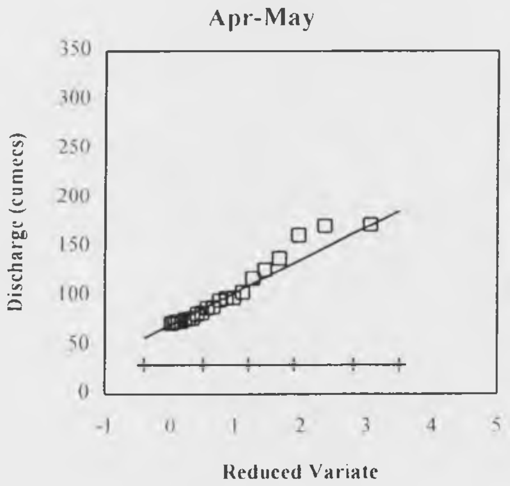


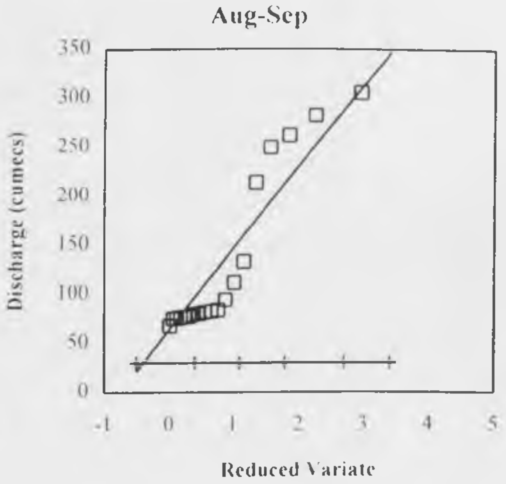


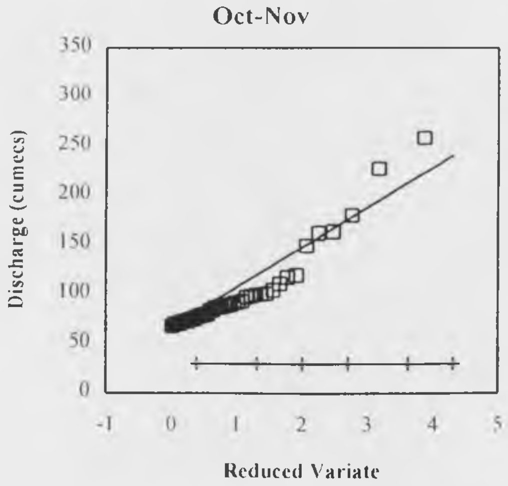
Appendix A (ii) : Seasonal frequency distributions - Nidd at Hunsingore 1934-1996





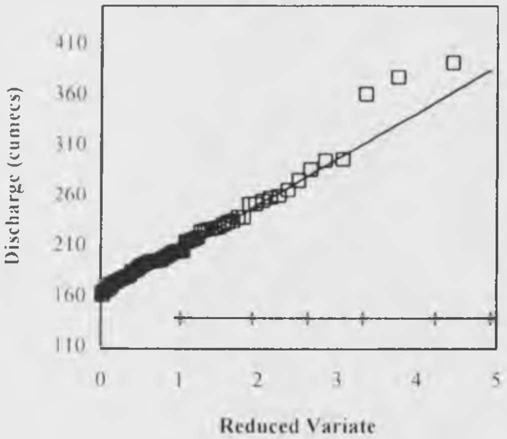




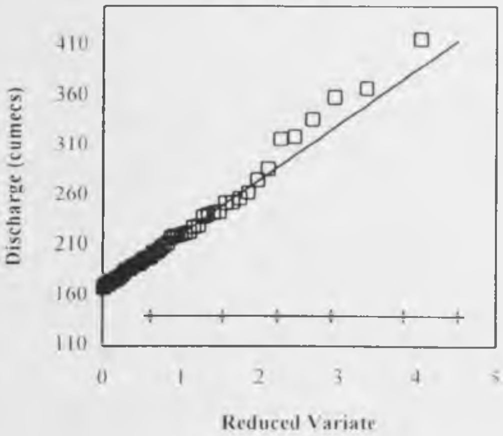


Appendix A (iii) : Seasonal frequency distributions - Wharfe at Flint Mill 1936-1996

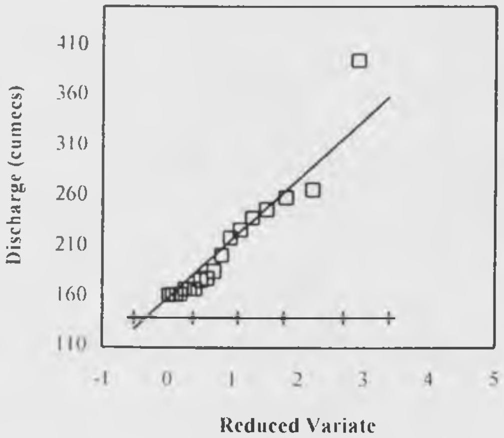
Dec-Jan



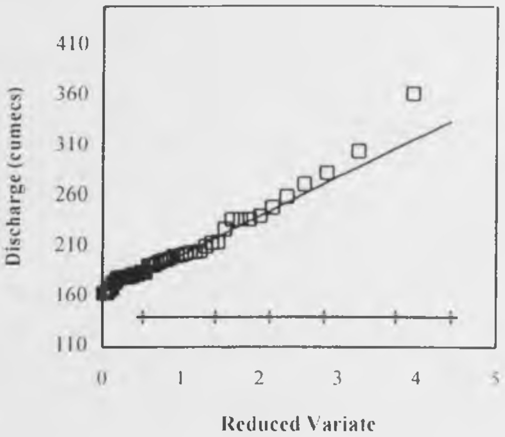
Feb-Mar



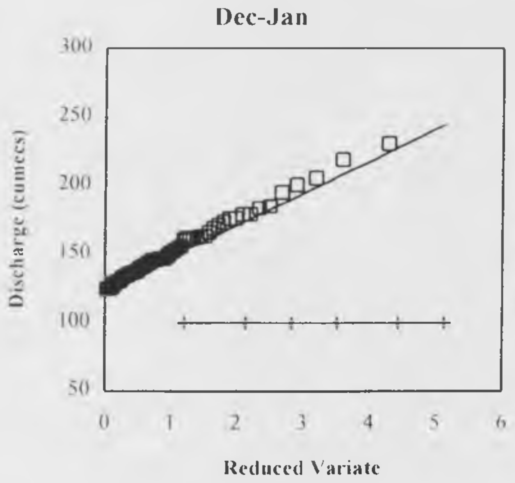
Aug-Sep

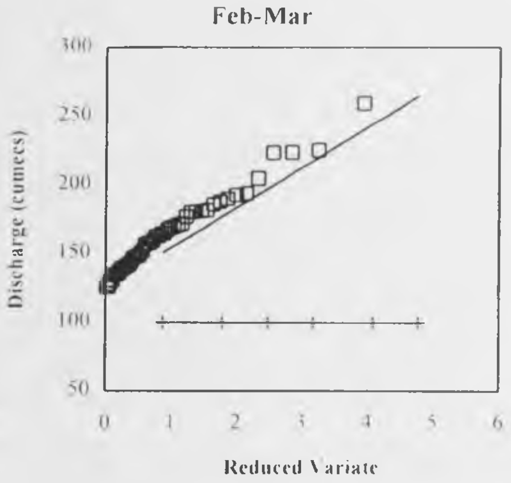


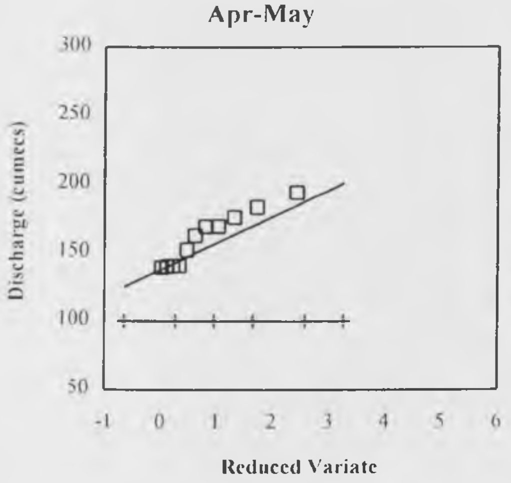
Oct-Nov

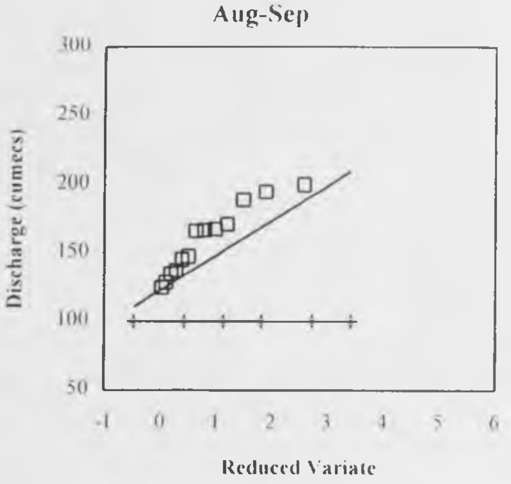


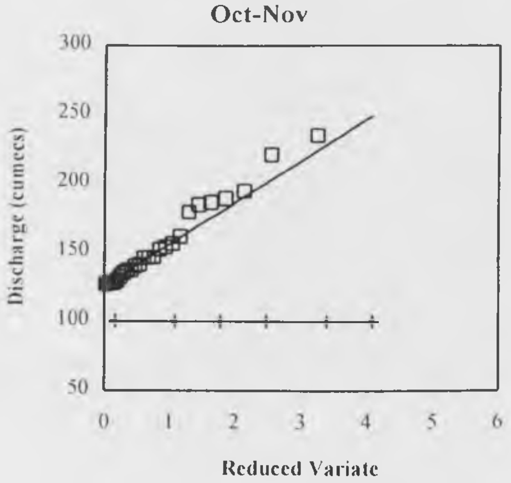
Appendix A (iv) : Seasonal frequency distributions - Swale at Crakehill 1955-1996



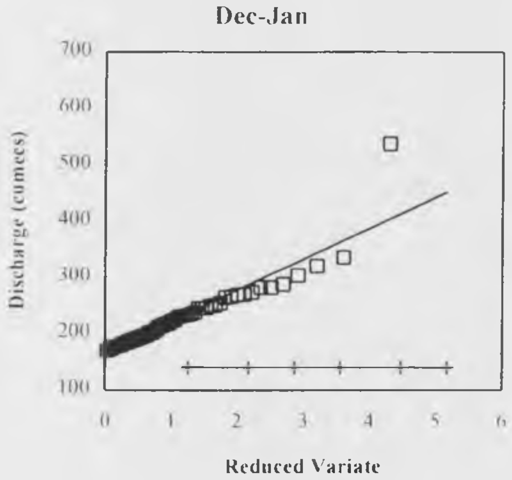


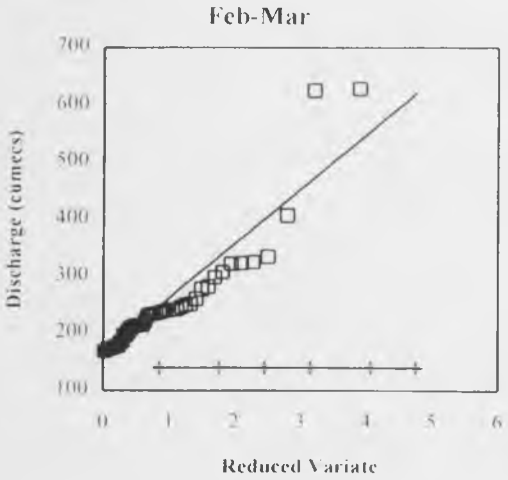


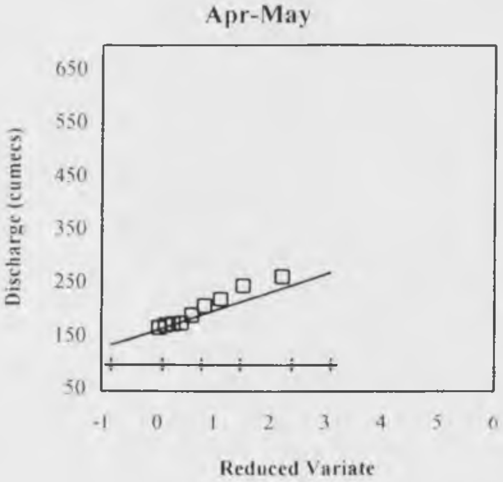


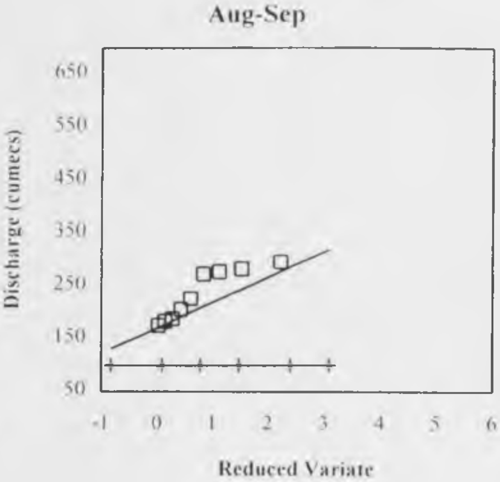


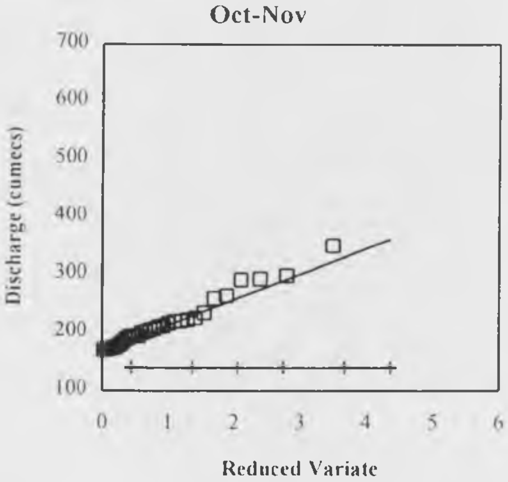
***Appendix A (v)** : Seasonal frequency distributions - Ure at Westwick 1956-1996*


Dec-Jan


Feb-Mar

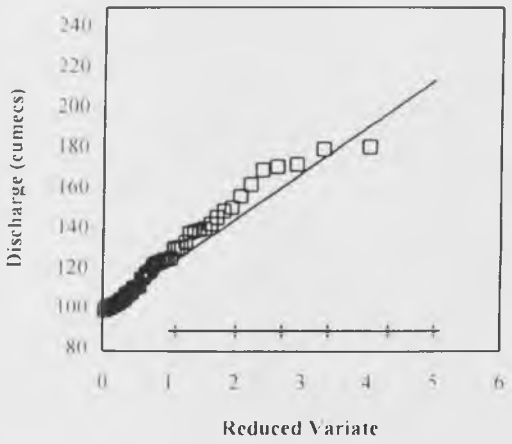

Apr-May


Aug-Sep

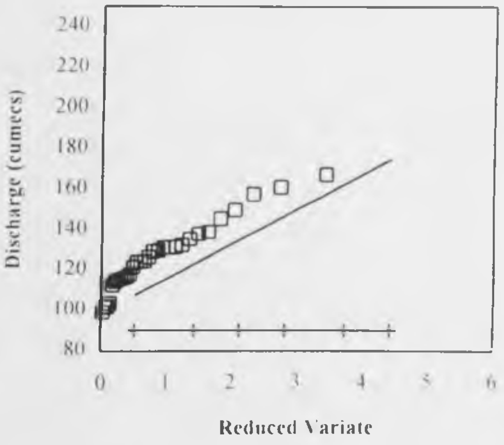

Oct-Nov

Appendix A (vi) : Seasonal frequency distributions - Aire at Armley 1961-1996

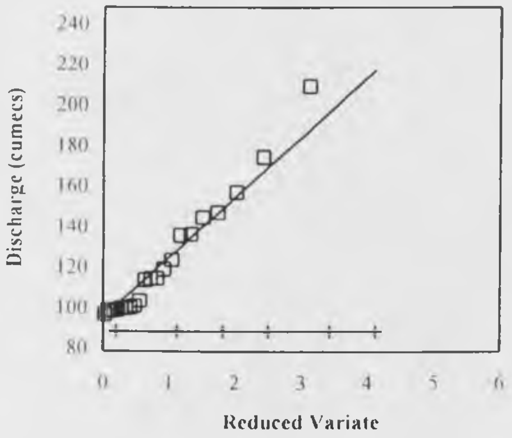
Dec-Jan



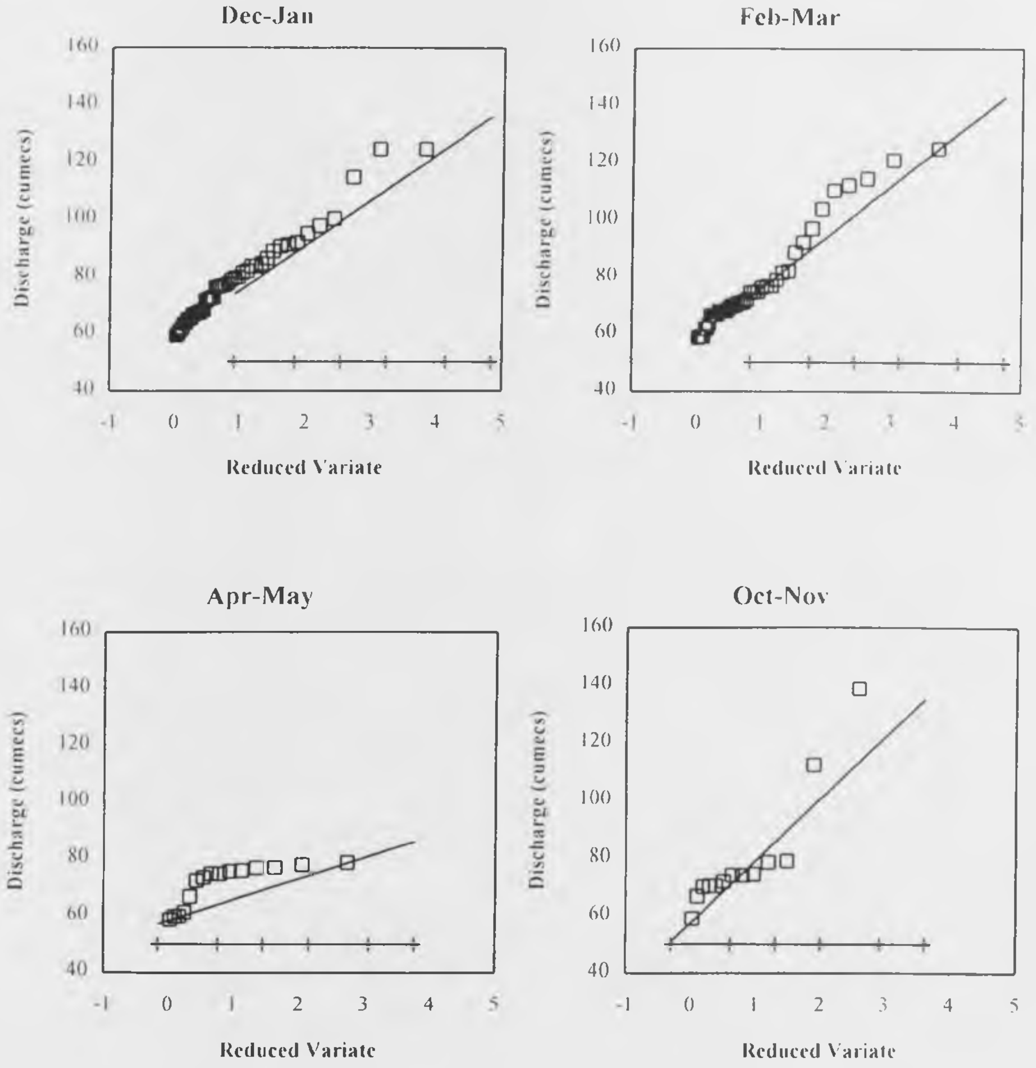
Feb-Mar



Oct-Nov



Appendix A (vii) *: Seasonal frequency distributions - Derwent at Buttercrambe 1962-1996*



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Appendix B(i) : River Aire Documentary Flood History 1068-1939

Year	Month	Day	Description	Source No.
1068/69			William the conqueror stopped for 3 weeks by swollen River Aire[49]	27,49,57
1322	Autumn		Meadow land flooded[57]	57
1594	Jan	5th	Sudden great flood[14]	14
1602	Jan	3rd	'the like not seen of 60 years before' [14]	14
1615	Mar	23rd	Thaw. Aire and Calder broke banks and caused much damage[14]	14
1615	Sep	16th	Heavy rain. Bridge at Keighley Destroyed[47]	47
1616	Sep	27th	Continuous rain for 36 hours with great E wind. Houses flooded at Leeds[14]	14
1680				33
1681			A great flood at Leeds[28]	28
1763	Jun	27th	Skipton 'greatest fall of rain ever known'[10]	10,28
1763	Dec	26th	Sudden thaw and heavy rain. Flooding at Leeds[17]	17,21,33
1766	July	21st	Disastrous storm[10]	10
1768	Jul		Flood carried away three bridges and did much damage at Leeds and Bradford[17]	17,28
1775	Oct	21st	Severe flooding throughout the Aire, several bridges destroyed[17]	17,21,28,30,33,41,59
1790	Dec		Sudden thaw and heavy rain, several bridges destroyed[17]	17,30
1795	Feb	9th	Heavy rains and sudden thaw[51]	17,28,30,33,51,54
1798	Summer		Severe storms. At Castleford the Aire rose by six feet in half an hour[9]	9,21
1799	Aug	16th	Rainstorm[9]	9,11,21,28,30,33
1806	Jan	16th	Leeds and Wakefield flooded[17]	17,30
1807			'destructive floods'[30]	30
1810	Jan		Flooding at Keighley[43]	43
1815	Dec	30th	Sudden thaw. Lower streets of Leeds flooded[17]	17,21,28,33
1816			'destructive floods'[30]	30

1822	Feb	3rd	Storm. Leeds flooded[17]	17,30
1823	Dec	21st	Lower streets in Leeds flooded[18]	28
1824	Dec	21st	Lower streets in Leeds flooded[17]	17,21,30
1825	Dec		Floods at Keighley[43]	43
1837	Dec	21st	Three days heavy rain. Four or five feet of water in some Leeds streets[17]	17
1840	Jan	25th	Heavy rains. Lower streets in Leeds flooded[17]	17,21
1846	April	6th	Level on stones near railway bridge	
1849	Oct	7th	Level on stones near railway bridge	
1856	Aug	9th	Two inches of rain at Leeds[17]	17
1857	Dec		Floods at Keighley[43]	43
1861	Feb	9th	Level on stones near railway bridge	
1866	Nov	17th	Serious damage below Castleford[59]	2,30,33,43,57,59
1867	Feb	7/8th	Flooding at Keighley - not as big as 1866[44]	44
1872	Jun		Severe thunderstorm, flooding at Keighley, Otley and Halifax[46]	46
1872	Oct		Floods in Airedale[46]	46
1872	Nov	18/20th	Floods throughout Yorkshire, very serious in Aire Valley[17]	17
1880	Dec		Flooding at Keighley. Rapid thaw[42]	42
1882	Feb	3rd	Leeds flooded[28]	21,28
1892	Oct	16th	Serious flooding in lower reaches[59]	57,59
1936	Dec	14th	Highest flood recorded in upper Aire Valley[59] Keighley flooded[40]	40,59
1939	Jan	15/16th	Castleford[59]	39,59

Appendix B(ii) : River Ouse at York Documentary Flood History 1263-1831

Year	Month	Description	Source No.
1263		Passed over end of Ouse Bridge, reached junction of Bridge Street and North Street[11]	11,52,56,58,59
1315	July	Floods surrounded the castle and washed away part of earthworks[11]. 'a huge and lasting one'[33]	11,30,33,59,60
1316		Flood water from the Ouse and Foss entered the moat and caused the curtain wall to collapse[32]	32,59
1360		Flooded underground prison so that it was useless for the custody of felons[32]	32
1550		Derwent and Ouse[33]	33
1564	January	Snow and great frost. Two arches of Ouse Bridge washed away.[11]	3,11,17,20,24,28,30,52,58,59,60
1615	March	Ouse ran down North Street and Skeldergate with great violence.[11] A ten-day peak. [33] Thaw[14]	1,4,11,14,16,28,33,52,58
1625		On City wall plaque	11,31,33,52,58,59
1636		On City wall plaque	11,31,33,58,59
1655		Ouse-Humber 'ye like scarce memorable'.[11]	11,13,16,33,53,56
1689	October	A mighty flood met spring tides. A very long frost.[11]	11,33,52,58
1715			11,33
1732	January	Bridge Street flooded[11]	11,33,52,56,58
1763	December	A great snowfall, rain and a high wind.[11]	11,16,31,33,56,58,59
1771	Nov	River Ouse 'n uncommon height'[55]	55
1783	February		58
1784		Thaw.[11]	11,16,21,28,33
1790	January	Thaw. Greatest since 1715.[11]	11,31
1794		Lower Ouse basin like a lake. 'On of the greatest floods ever known.[11]	11,24,33
1795	February	Snow.[11]	3,11,52,58
1809			58
1822	February	Ouse and all other rivers.[11]	11,17,33,59
1831	February	Frost snow and rain.[11] Third highest mark on City Walls.[33]	11,31,33,52,58,59

Level data is available from 1831 onwards

Appendix B(iii) : River Calder Documentary Flood History 1308-1967

Year	Month	Day	Description	Source No.
1308			Damage to wooded bridge at bottom of Kirkgate[49]	49
1330	Dec		Prolonged heavy rain. Bridge destroted[49]	49
1615	Mar	23rd	Thaw. Calder broke banks[14]	14
1615	Sept	16th	Bridges at Elland and Keighely destroyed [47,59]	47,59
1616	Sept	27th	38 hours continuous rain with E wind. Calder 'very great'[14]	14
1673	Sept	11th	Bridge at Sowerby Bridge damaged[47]	47
1674	Oct	31st	Water seven yards deep either side of Wakefield Bridge[51]	51
1680	Aug	26th	Wakefield, storm.[21]	21
1722	May	18th	Ripponden near Halifax[17]	17,21,33,37,47
1729	Nov	8th	Severe flooding at Dewsbury and Wakefield[59]	51,59
1738	May	7th	Severe thunderstorm. Flood forced its way into a chapel at Holmfirth[23]	23
1767	Dec	7/8th	Severe damage at Dewsbury. Higher than 1729[59]	33,59
1775			Severe flooding at Castleford[59]	59
1777	July	23rd	Thunderstorm, Holmfirth[23]	23
1795			Heavy rains and sudden thaw[51]	51,54
1799	Aug	17th	Serious flooding at Sowerby Bridge[59]	21,28,47,59
1821	Sept	21st	Black-Sike Mill reservoir Burst[17]	17
1822	May	20th	Holmfirth[18], severe thunderstorm[21]	21,28
1837	Dec	22nd	Highest flood in half century 1810-1860. Damage along whole length of River Calder[59]	51,54,59
1844	June	24th	Thunderstorm. Flooding at Halifax and Huddersfield[21]	21
1852	Feb	5th	Bilberry Reservoir burst - Holmfirth[17]	17,21
1855	Oct	26th	Prolonged heavy rain[48]	48
1857	Aug	14th	Ripponden[17]	17,33
1859	Aug	7th	Heavy rains. Flood at Hebden Bridge[48]	48
1866	Nov	17th	In lower reaches this was the highest flood recorded (except possibly 1775)[59]	2,51,59
1892	Oct	15th	Lower and middle reaches[59]	59

1901	Nov	12th	Severe flooding in upper reaches[59]	59
1916	Aug	14th	Todmorden flooded[5]	5
1931	Nov	4th	Todmorden flooded[5]	5
1938	Aug	12th	Cloudburst. Chaos at Walsden[5]	5
1944	Jan	23rd	Highest flood in 50 years in middle reaches[59]	59
1946	Sep	20th	Worst flood since 1866[59]	25,59
1960	Nov	27th	Extensive flooding along Calder Valley[59]	59
1967	Oct	17th	Flooding at Wakefield and Dewsbury[59]	59

Local portfolio No. 128, compiled by **J.B.Walker**. The Halifax Guardian.

- Levels from Mr W. Oates of Mirfield in February 1853, *River Calder.*

1799	Aug	2nd	16	3
1806	Jan	6th	16	4
1815	Dec	6	15	4
1818	Jan	-	13	3
1824	Dec	24	12	7
1825	Nov	28	12	0

No flood from this time reached 12ft until...

1833	Nov	22	12	1
1834	Jan	27	13	1
1835	Jan	16	12	8
1836	Mar	17	3	10
1837	Feb	23	12	6
1837	Dec	20	15	0
1838	Oct	29	12	2
1839	Nov	29	12	2
1840	Jan	24	7	11
1840	Jan	26	12	3
1840	Aug	17	12	6
1840	Nov	16	12	5
1843	Oct	28	12	4
1845	Oct	28	12	8
1845	Dec	28	13	6
1852	Feb	5	13	6

- 'In addition to these floods, Mr Oates informed us that during the same period, thirty-two other floods were registered at Mirfield, wherein the water rose above six feet higher than the dam stones near Mirfield; but none of these attained to 12 feet; they may be excluded from the list of great floods.'

Appendix B(iv) : River Derwent Documentary Flood History 1550-1932

Year	Month	Day	Description	Source No.
1550				33
1754			Rye flood[22]	22
1787			Borobeck flood[22]	22
1799	Sep		Hundreds of acres flooded[26]	26
1846			Extensive flooding in Ryedale[59]	59
1866	Sep			34
1866	Nov	16th	Heavy rain[2]	2
1869	Dec		Thunderstorm. North riding rivers rose rapidly[34]	34
1892	Oct		Heavy flooding[34]	34
1914			Flooding at Pickering[29]	29
1925	Dec		Pickering flooded[34]	34
1927	Aug	25th	Flooding at Pickering[29]	29
1931	Sep		Disastrous floods in Ryedale and Eskdale[59]	34,59
1932	May	22nd	Flooding at Pickering[29]	29

Appendix B(v) : River Don Documentary Flood History 1655-1941

Year	Month	Day	Description	Source No.
1655			Extensive Flooding at Ouse confluence[59]	59
1729	Jun	21st	Flood at Sheffield[14]	14
1755	Aug	5th	Great flood - washed away several bridges[35]	35
1768	Nov		Great floods[35]	35
1797	Aug	17th	Don and Sheaf 'swelled to an amazing height'[35]	35
1799	Aug	7th	Don and Sheaf overflowed[35]	35
1806	Jan	16th	One of the highest floods ever remembered[35]	35
1807	May	2nd	Rapid rise[17]	17
1834	Jul			35
1850	Jan		Lower Don[59]	59
1866	Nov	16th	Heavy rain[2]	2
1886	May	14th	Highest level in 50 year period[59]	59
1892	Oct	16th	Lower reaches[59]	59
1931	Sep	4th		59
1932	May	24th	Extreme flooding in Doncaster[59]	59
1941	Oct	1st	Highest recorded discharge through Doncaster[59]	59

Appendix B(vi) : River Wharfe Documentary Flood History 1673-1965

Year	Month	Day	Description	Source No.
1673	Sep	11th	Bridges between Kettlewell and Otley destroyed[50]	6,8,28,50
1686			Kettlewell and Starbotton 'the height of an ordinary church steeple' [12]	12,17,19,33
1758			Flood at Tadcaster church[37]	37
1857	Aug			33
1866	Nov	16th	Heavy rain[2]	2
1868	Jun	8th	'disastrous flood' in uplands[36]	36
1869	Feb			18
1869	Dec	18th	Kettlewell. Largest in 10 years, 3 inches higher that Feb 1869[18]	18
1872	Jun	18th	'damage on east side of Wharfedale'[18]	18,33
1874	Oct	21st	Largest in 16 years[18]	18
1881	Mar	3rd	Three days of snow. Uplands [33,36]	33,36
1886	Nov			43
1891	Aug	25th	Uplands. 'one of the biggest floods of the present century'[36]	36
1900	Jul	12th	Ilkley. 5.4 to 6 inches of rain[7]	7
1965	Dec			59

Appendix B(vii) : River Swale Documentary Flood History 1673-1953

Compiled from :
Williams, H.B. 1957. *Flooding Characteristics of the River Swale.* Unpublished PhD Theses, Department of Civil Engineering, University of Leeds.

Year	Month	Day	Description
1673	Sep	11th	Brompton-on-Swale flooded, two bridges washed away.
1682	Jul		Flooding around Brompton-on-Swale.
1683	Dec	19th	Reeth bridge damaged.
1697	Winter		Several bridges damaged.
1701	Jun	25th	Cloudburst. Destroyed bridge over Grinton Beck.
1732	Feb	2nd	Flooding at Brompton-on-Swale.
1753	Jan	17th	Brompton bridge washed away.
1771	Nov	16th	Serious flooding throughout northern England. 'damage about Richmond terrible'. Many bridges lost or damaged in the Swale.
1814	Dec	10th	Heavy rain and thaw, 'greatest flood ever known (except that of 1771)'
1821	Apr	25th	Thunderstorm. Rapid rise of the river.
1822	Feb	2nd	Bridge over Gunnerside Beck destroyed. At Topcliffe this flood was higher than in 1947.
1828	Jul	13th	'The greatest flood ever known at this season'. Isles Bridge damaged.
1835	Mar	11th	Thaw.
1866	Nov	16th	Heavy rainfall. Flooding near Swale Nab.
1878	Nov	15th	Record flood at Thirsk.
1881	Mar	9th	Banks broke at Langton and Scruton. Flooding throughout the Swale.
1882	Feb		Highest recorded levels at Topcliffe[59]
1883	Jan	29th	Thaw. Severe flooding throughout Swaledale, and Catterick. Many bridges destroyed. 'The river rose 30ft at Keld'
1888	Jul	25th	Cloudburst. 'one of the biggest summer floods ever known swept down Swaledale'.
1890	Jan	25th	Gunnerside bridge washed away.
1892	Sep	1st	Swaledale and Richmond flooded.
1892	Oct	15th	Heavy rain. Swale burst banks at Scruton, Morton Bridge and

			Fairholme. Flooding at Topcliffe.
1894-95			8ft above normal at Gunnerside Bridge
1897	Mar		Catterick flooded, Langton Bridge damaged
1899	July	12th	Cloudburst. Upper Swaledale. Many bridges damaged or destroyed, at Keld, Thwaite and Muker.
1900	Oct	27th	Brompton-on-Swale flooded
1908	Jun	3rd	Cloudburst.
1910	Feb	17th	Thaw and heavy rain, with strong SW wind. Low lying land flooded.
1914	Jun	10th	Cloudburst above Gunnerside. Flooding at Gunnerside and Topcliffe.
1916	Dec	29th	Rain on snow. Reeth flooded.
1925	Jan	1st	Flooding at Reeth, Grinton, Langton and Brompton-on-Swale.
1927	Sep	21st	Flooding worst near Northallerton. Also serious flooding at Kirkby Fleetham and Morton-on-Swale. Topcliffe also flooded
1930	Jul	22nd	Northallerton flooded.
1931	Sep	5th	Swale overflowed at Myton.
1931			Cloudburst. Catterick flooded.
1936	Dec	14th	Heavy rainfall. Reeth, Grinton, Scruton and Morton flooded.
1941	Feb	28th	Snowmelt. 'Similar to 1947 flood, being an inch or two higher'
1944	Apr		Flooding at Richmond.
1946	Jun		Heavy rain.
1947	Mar	22nd	River only a few feet from the top of Topcliffe Bridge. Flooding throughout the Swale and Yorkshire.
1950	Feb	15th	'The biggest flood in 25 years' submerged large areas of Swaledale.
1950	Sep	5th	Flooding at Keld, Grinton and Richmond.
1953	Summer		Flood at Muker.

Appendix B(viii) : River Ure Documentary Flood History 1732-1927

Year	**Month**	**Day**	**Description**	**Source No.**
1732	Feb	2nd	Bridge at Masham washed away[18]	18
1763	Dec		Heavy snowfall and long duration rainfall[59]	59
1771			Greatest for many centuries[59]	59
1822	Feb	2nd	Masham 'great flood'[18]	18
1866	Nov	16th	Heavy rain[2] Boroughbridge flooded[55]	2,55
1868	Feb		High levels recorded[59]	59
1883	Jan	29th	Boroughbridge flooded[55]	55
1927	Sep	21st		55

Appendix B(ix) : River Nidd Documentary Flood History 1763-1881

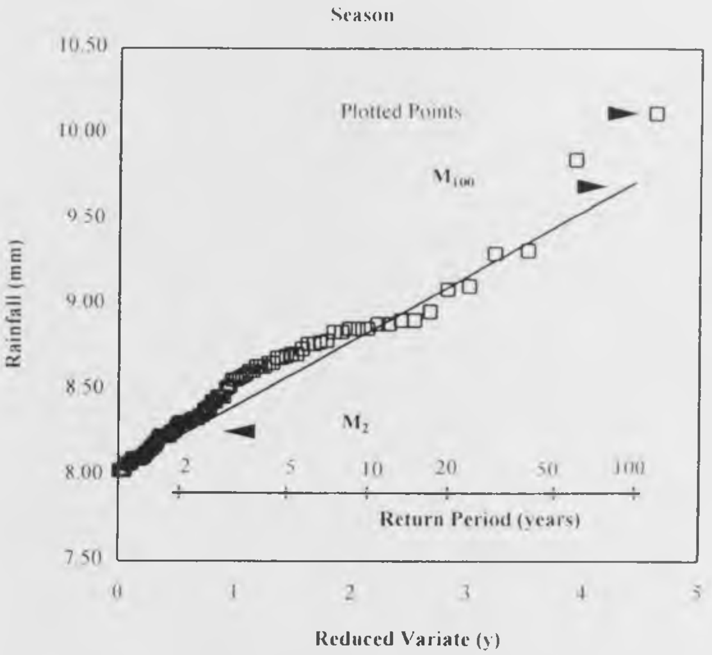
Year	Month	Day	Description	Source No.
1763	Jul		Ramsgill flooded[33]	33
1764	Jul	4th	Thunderstorm, Ramsgill flooded[7]	7,38
1777	Jul		Ramsgill flooded[33]	18,33
1825	May	6th	Severe flooding around Pately Bridge[18]	18
1852	Sep	29th		18
1866	Nov	16th	Heavy rain[2]	2
1868	Feb	1st	A foot higher than 1825[18]	18
1872	Jun			33
1881	Jul	6th		18
1881	Nov	28th		18

Heights above Mill threshold, Pately Bridge

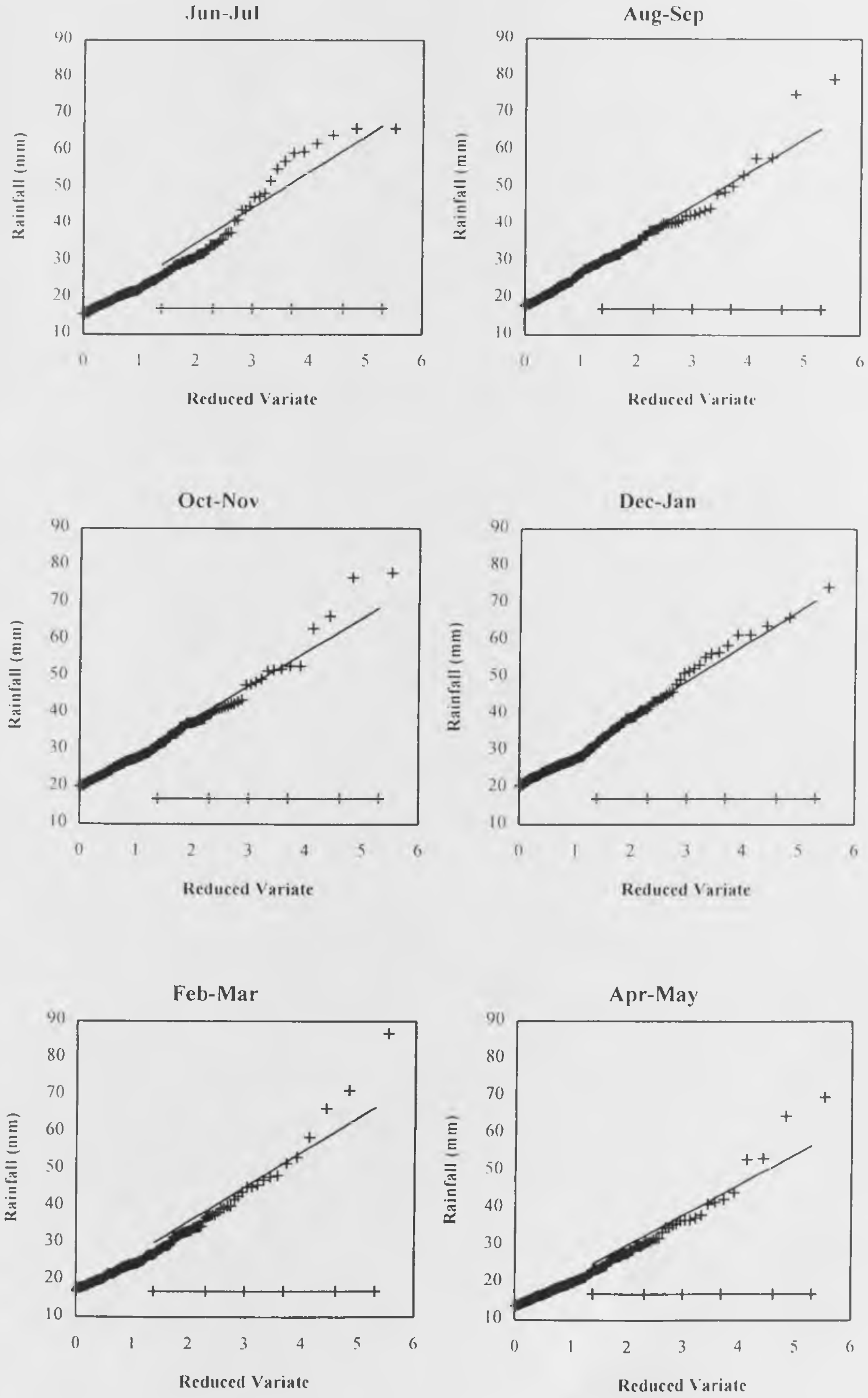
Feb 1	1868	3.6
May 6	1825	2.6
Sep 29	1852	2.0
Jul 4	1777	1.7
Jul 6	1881	0.6
Nov 28	1881	0.9

Between July 6th and Nov 28th 1881 a series of seven floods occurred, with the largest on 28th Nov[27]

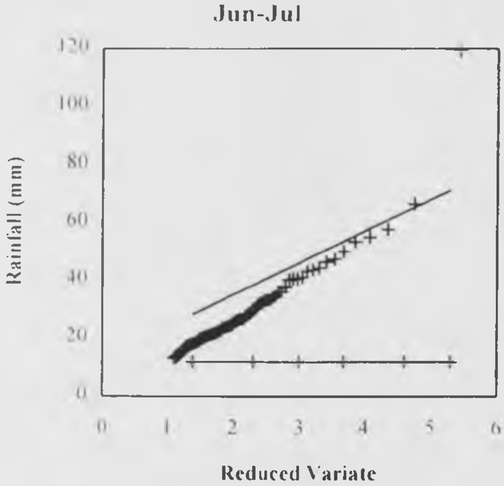
Appendix C : *Key to rainfall frequency distribution diagrams in Appendix C(i) - C(v)*

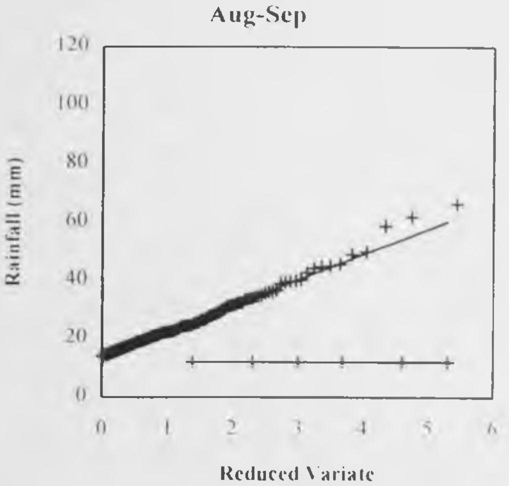


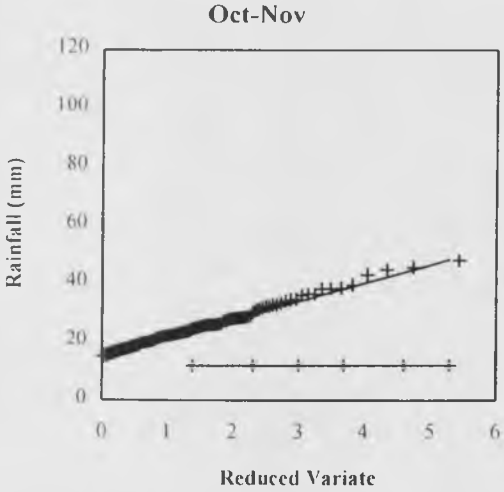
Appendix C (i) : Seasonal frequency distributions (Rainfall) - Blackmoorfoot 1873-1996

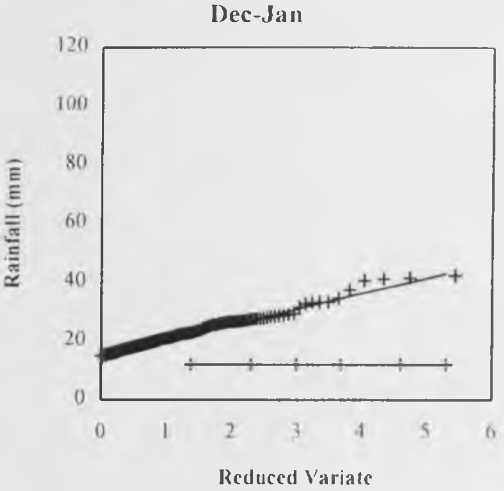


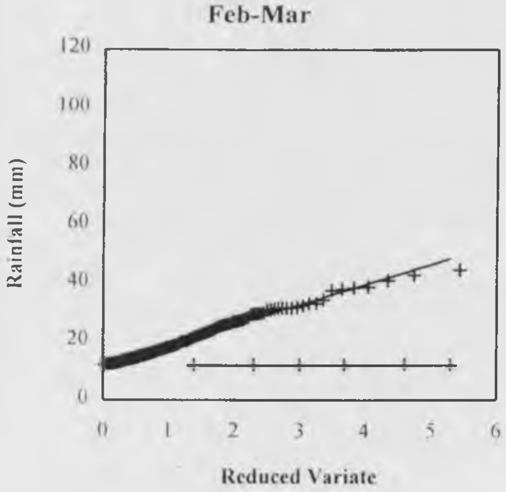
Appendix C (ii) : Seasonal frequency distributions (Rainfall) - Sheffield Weston Park 1883-1996

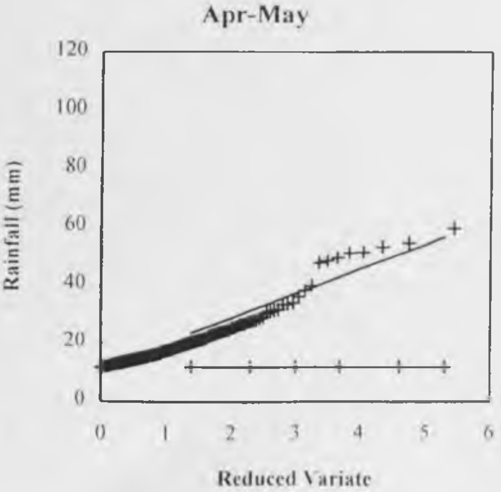

Jun-Jul


Aug-Sep

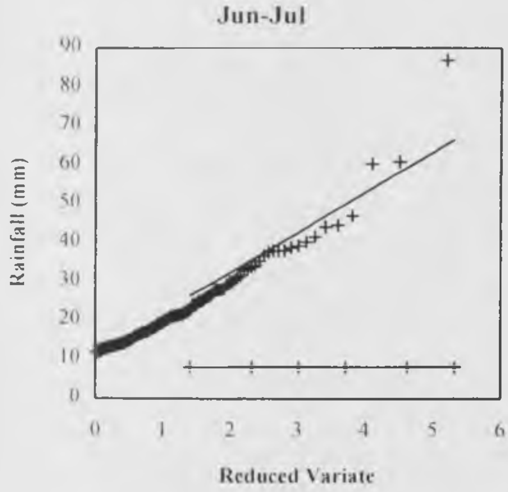

Oct-Nov

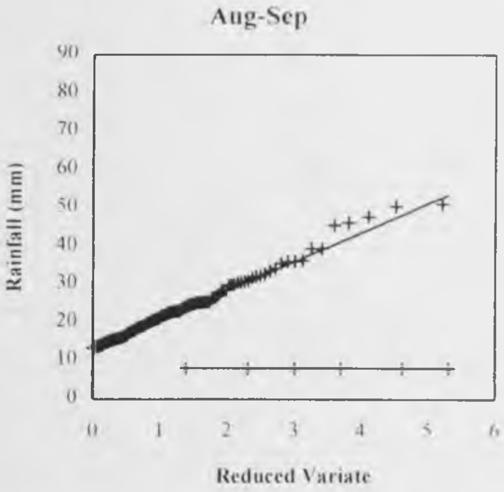

Dec-Jan

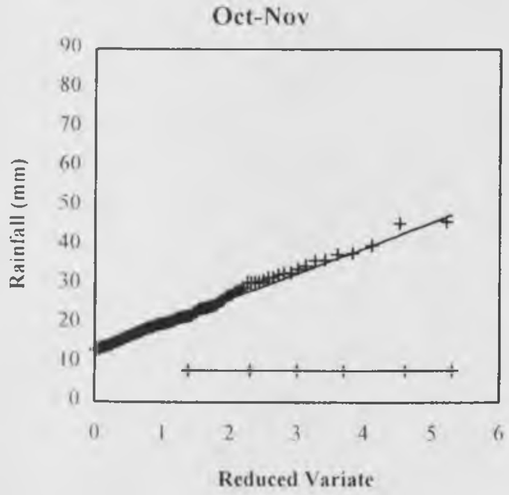

Feb-Mar

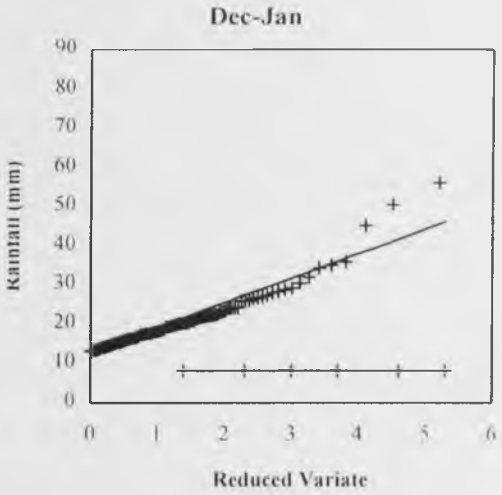

Apr-May

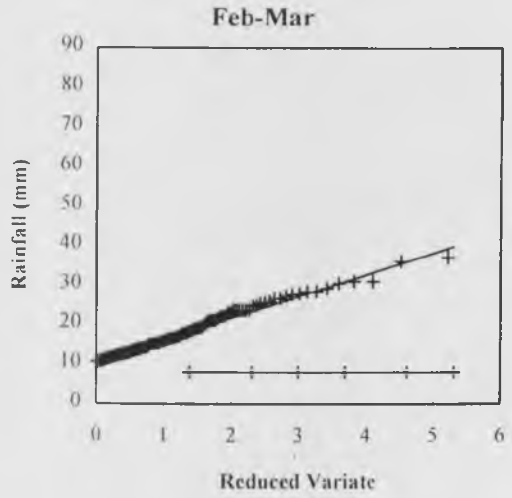
Appendix C (iii) : Seasonal frequency distributions (Rainfall) - Chesterfield 1906-1996

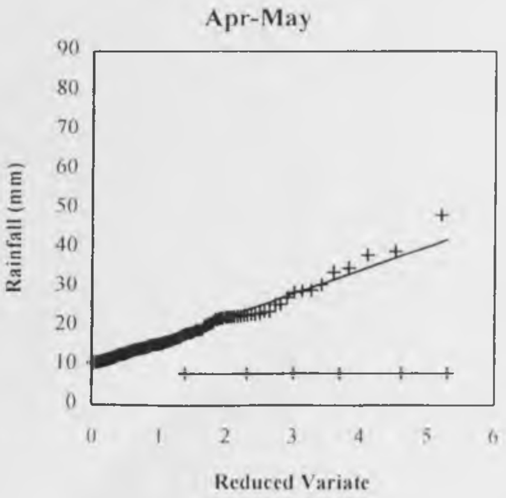




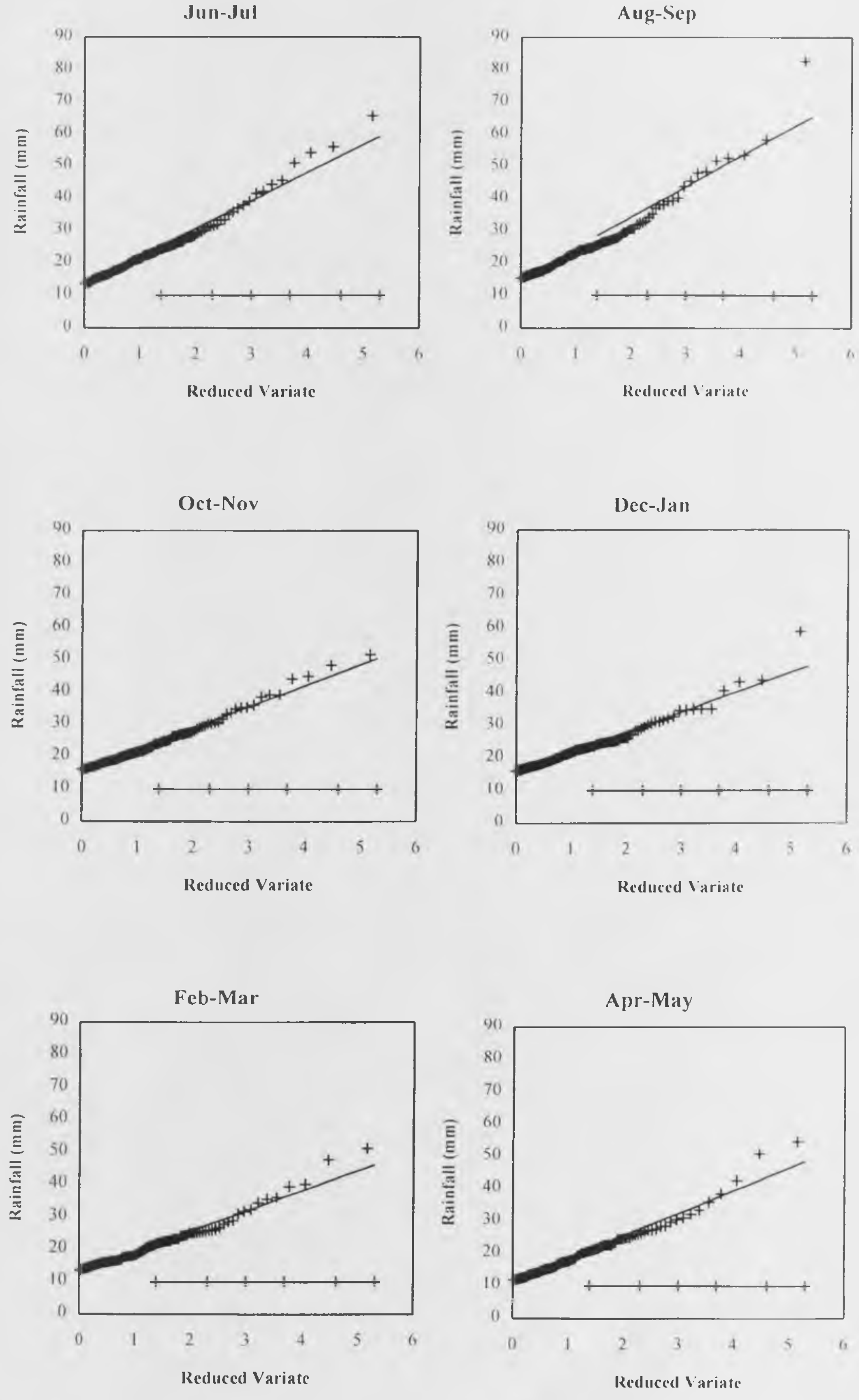




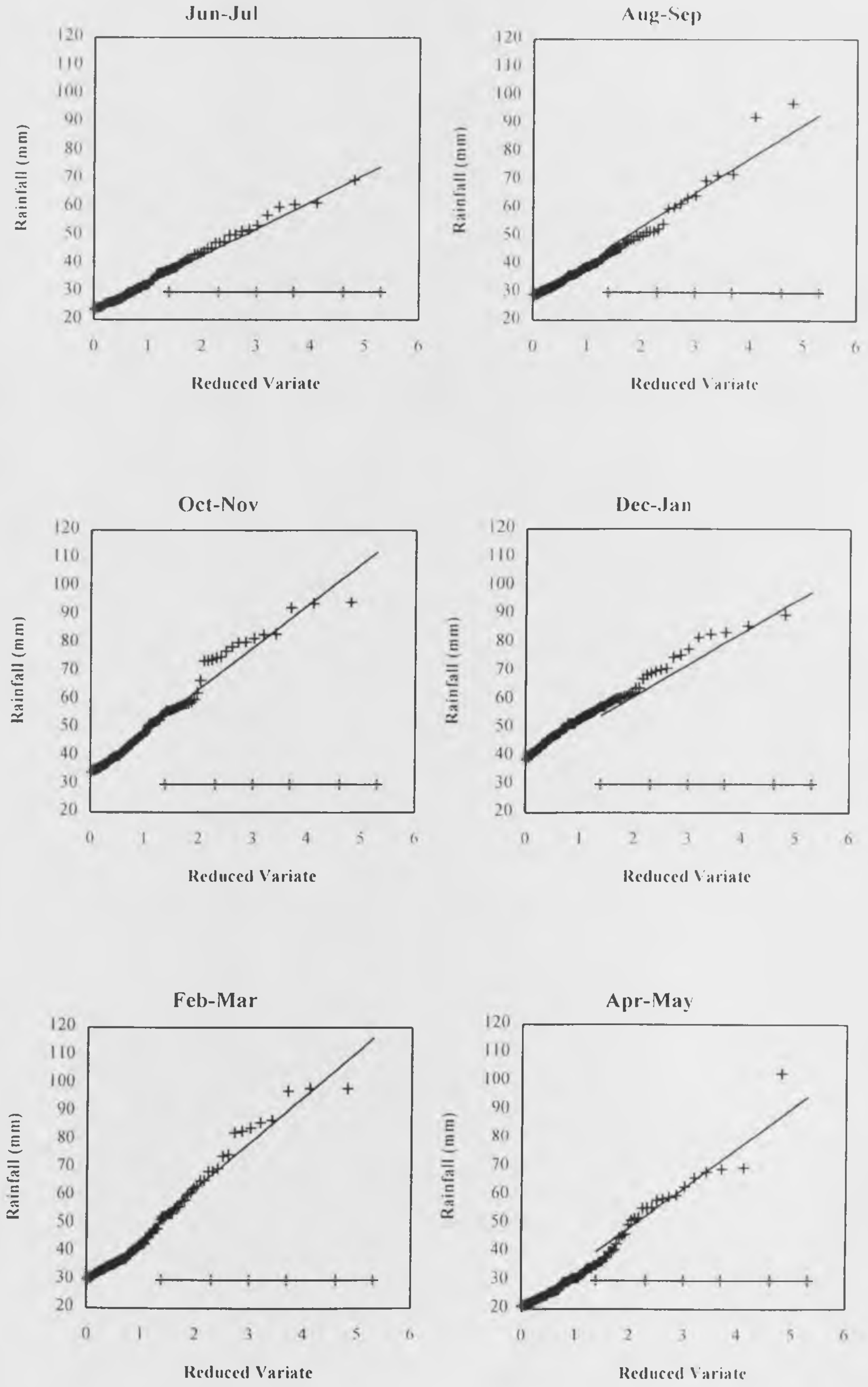




Appendix C (iv) : Seasonal frequency distributions (Rainfall) - Bradford Lister Park 1911-1996

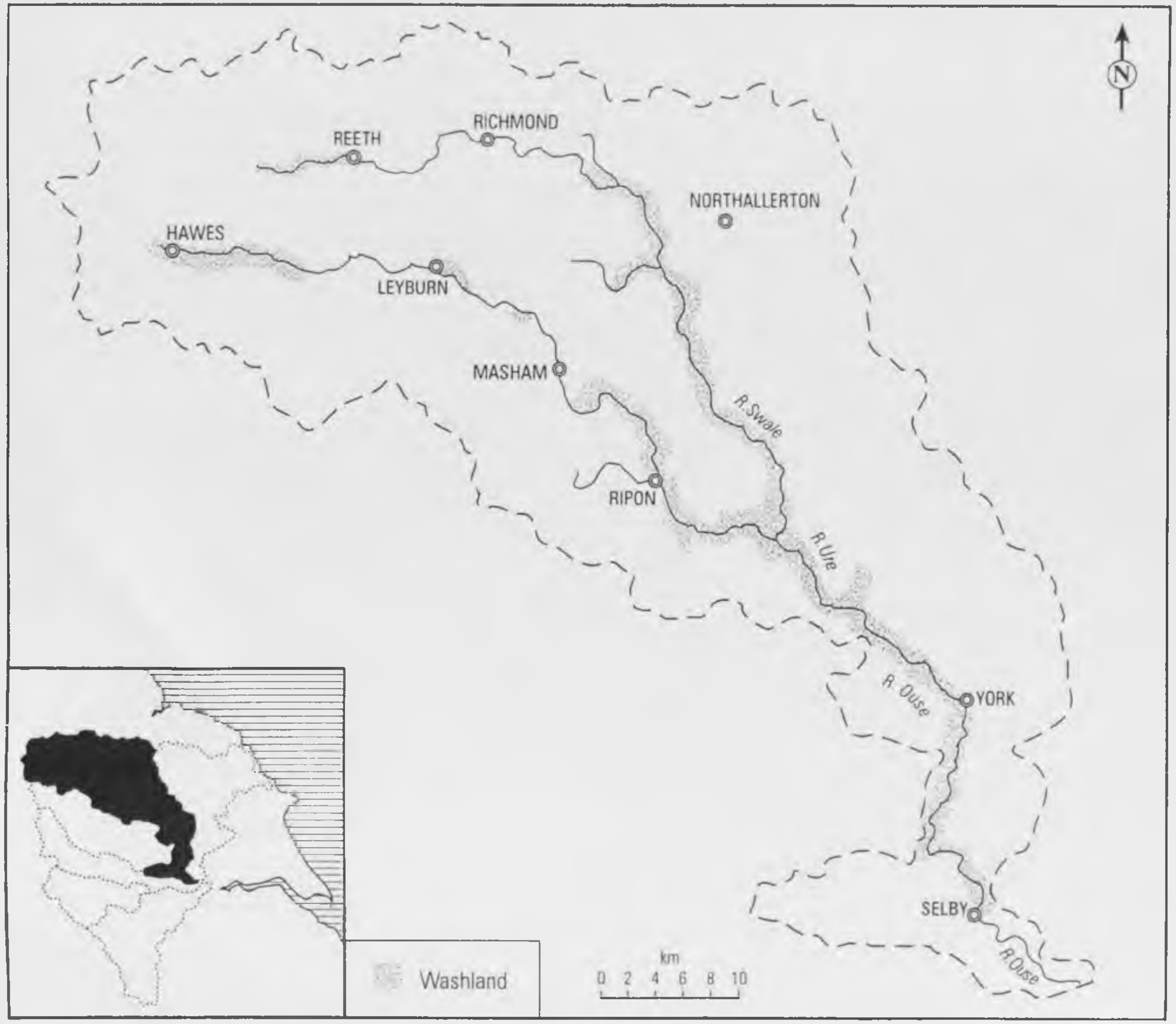


Appendix C (v) : Seasonal frequency distributions (Rainfall) - Moorland Cottage 1936-1995

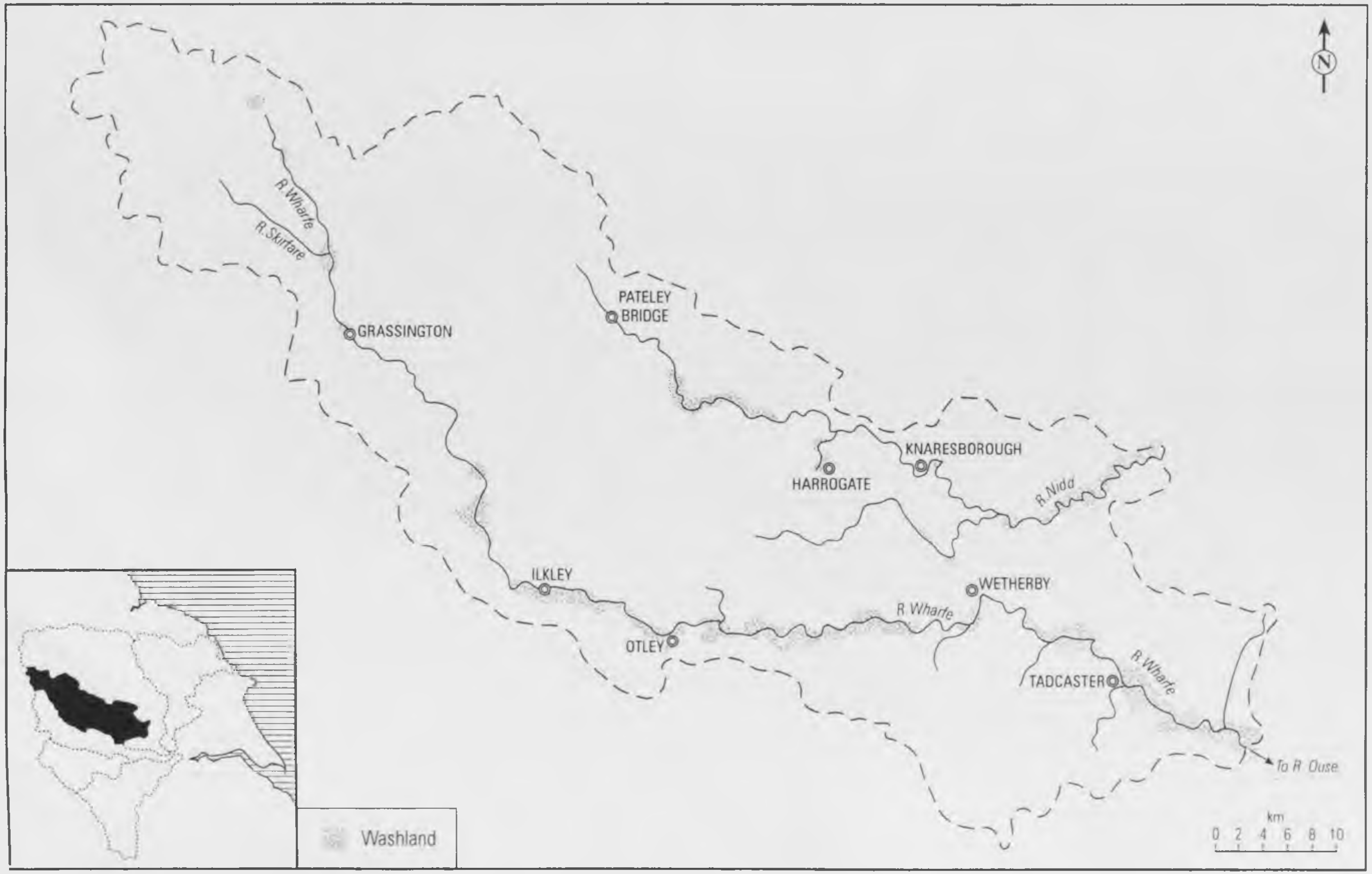


Appendix D(i): *Washlands in the Derwent catchment*

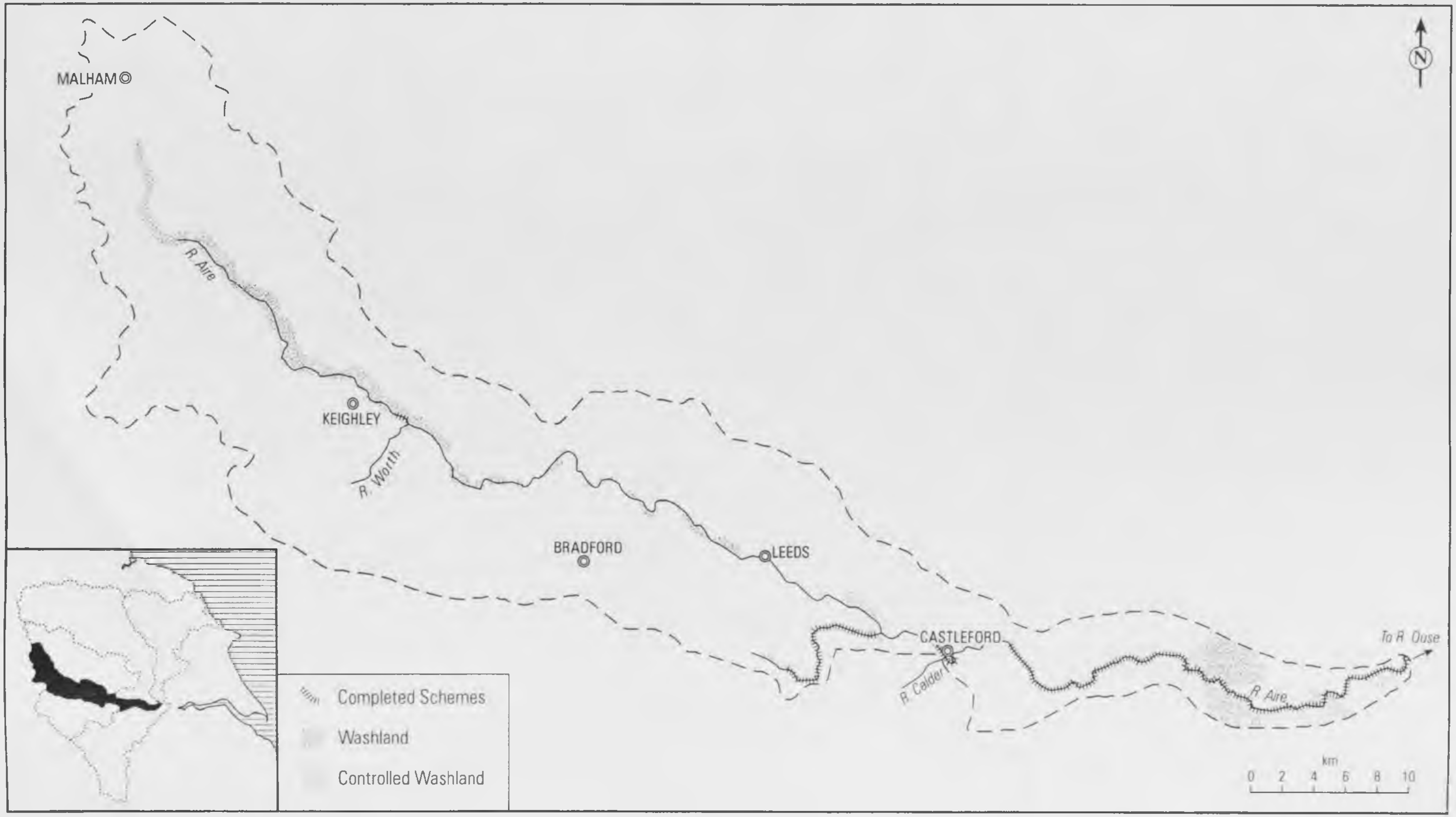
Appendix D(ii): *Washlands in the Swale, Ure and Ouse catchments*



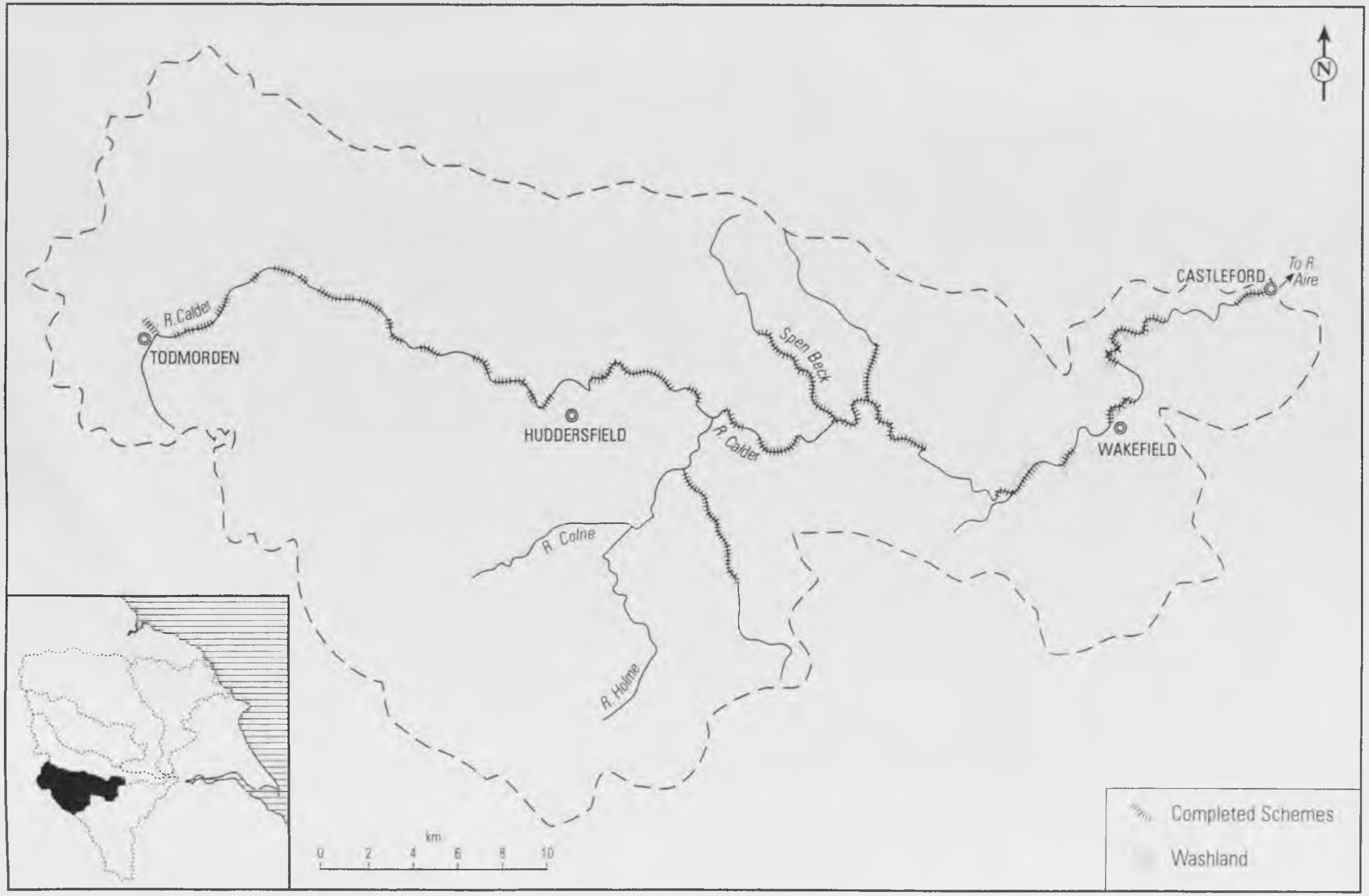
***Appendix D(iii):** Washlands in the Nidd and Wharfe catchments*



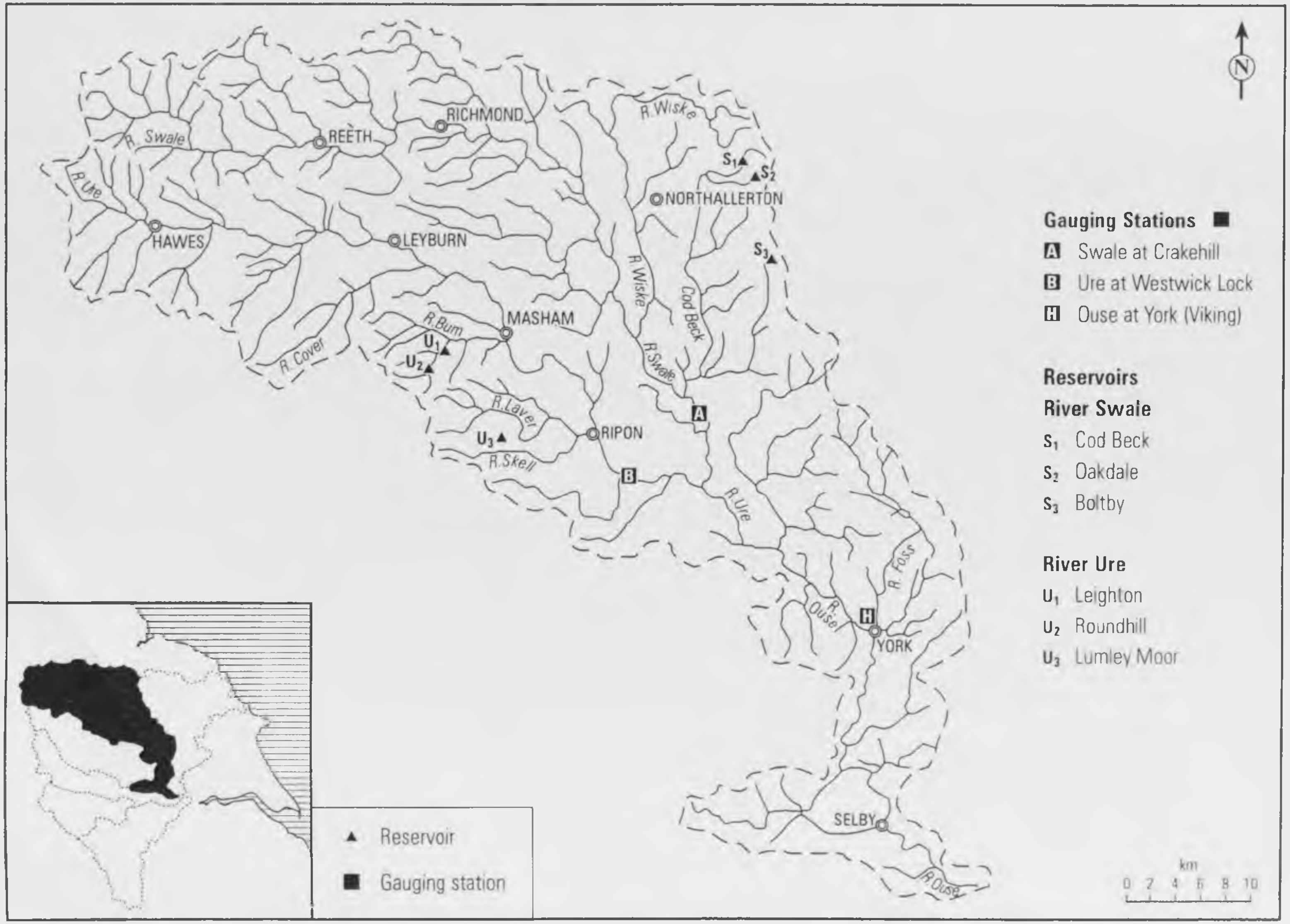
Appendix D(iv): *Completed flood defence schemes and washlands in the Aire catchment*



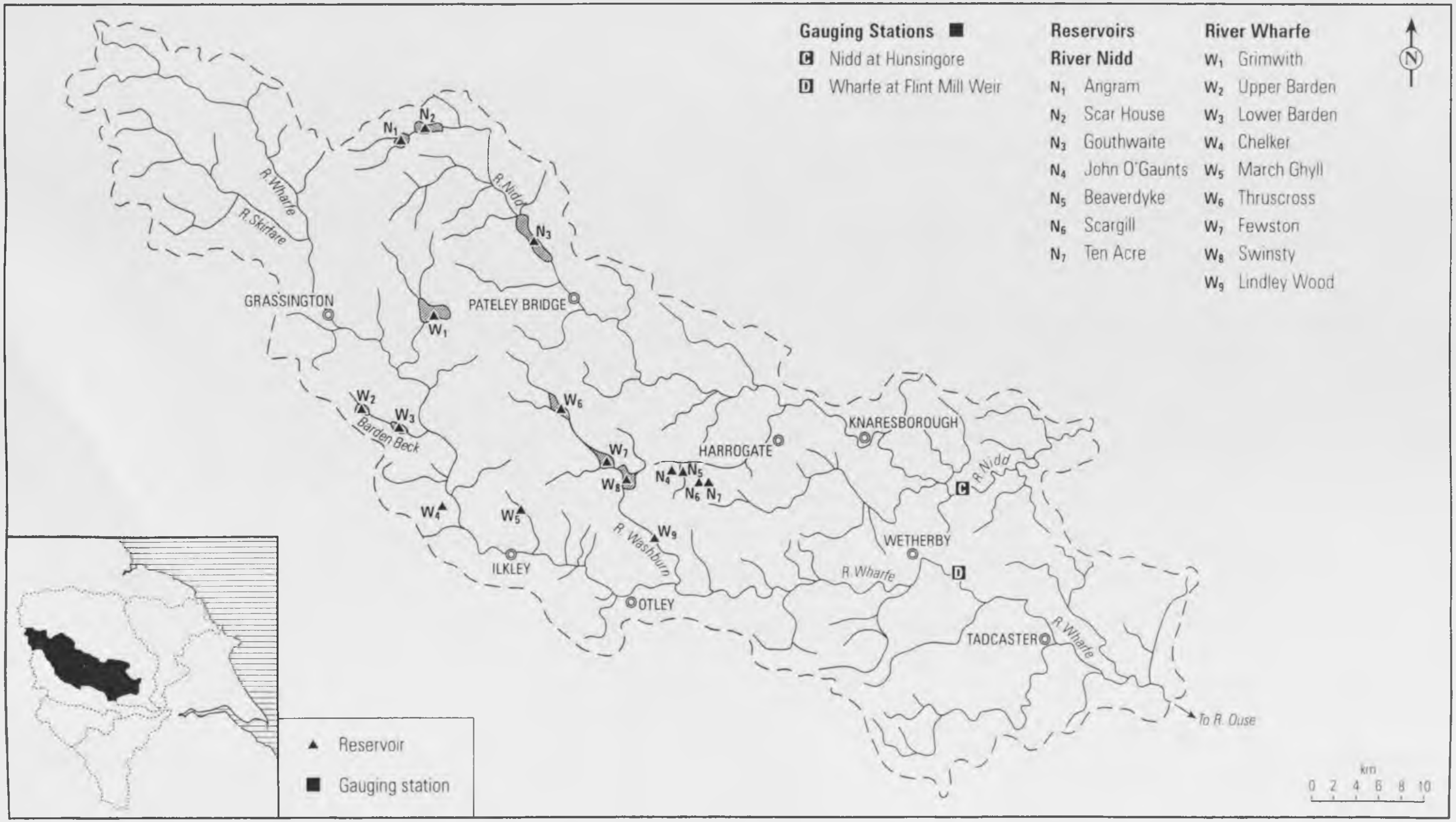
Appendix D(v): *Completed flood defence schemes and washlands in the Calder catchment*



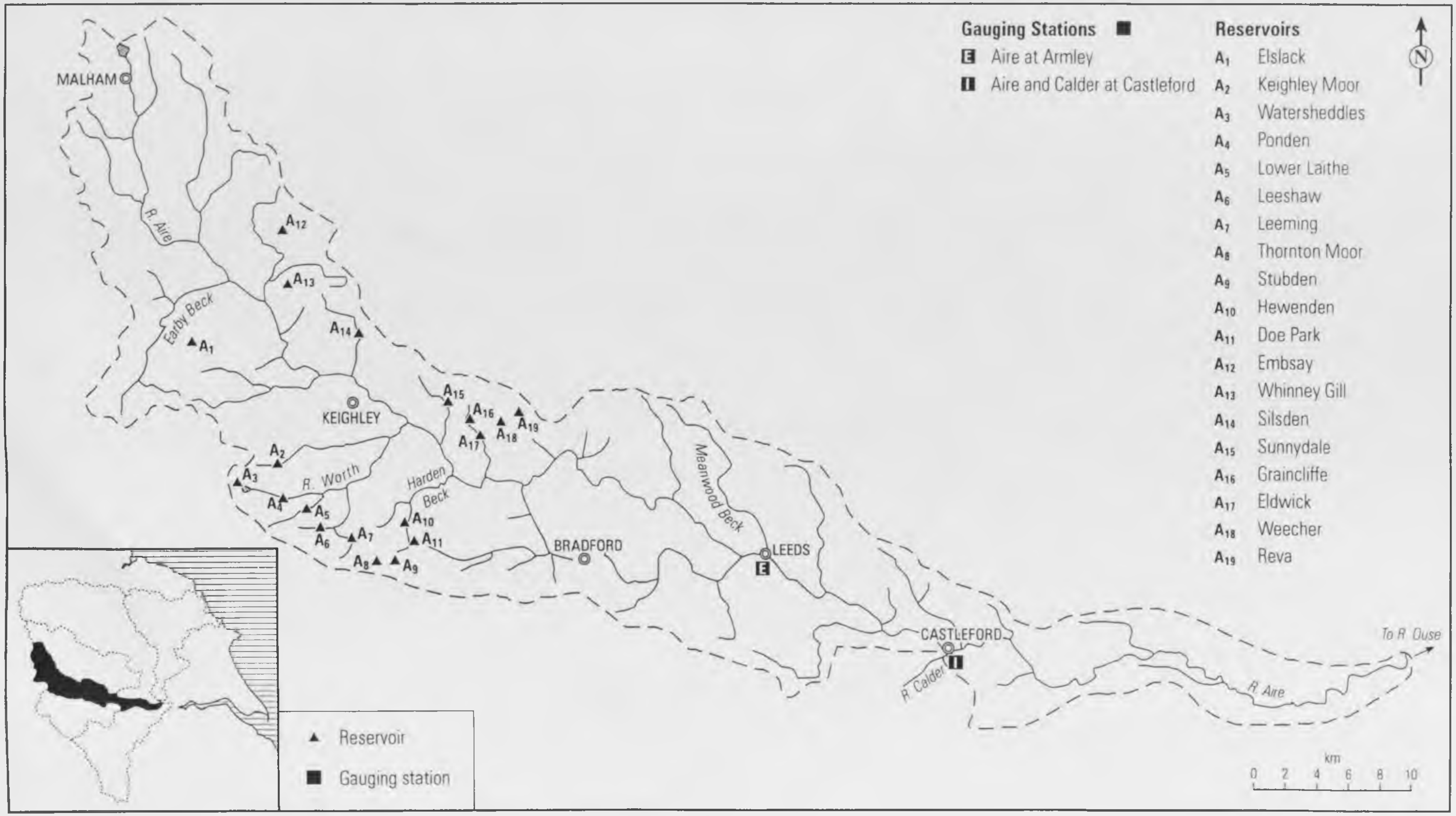
Appendix E(i): *Reservoirs in the Swale, Ure and Ouse catchments*



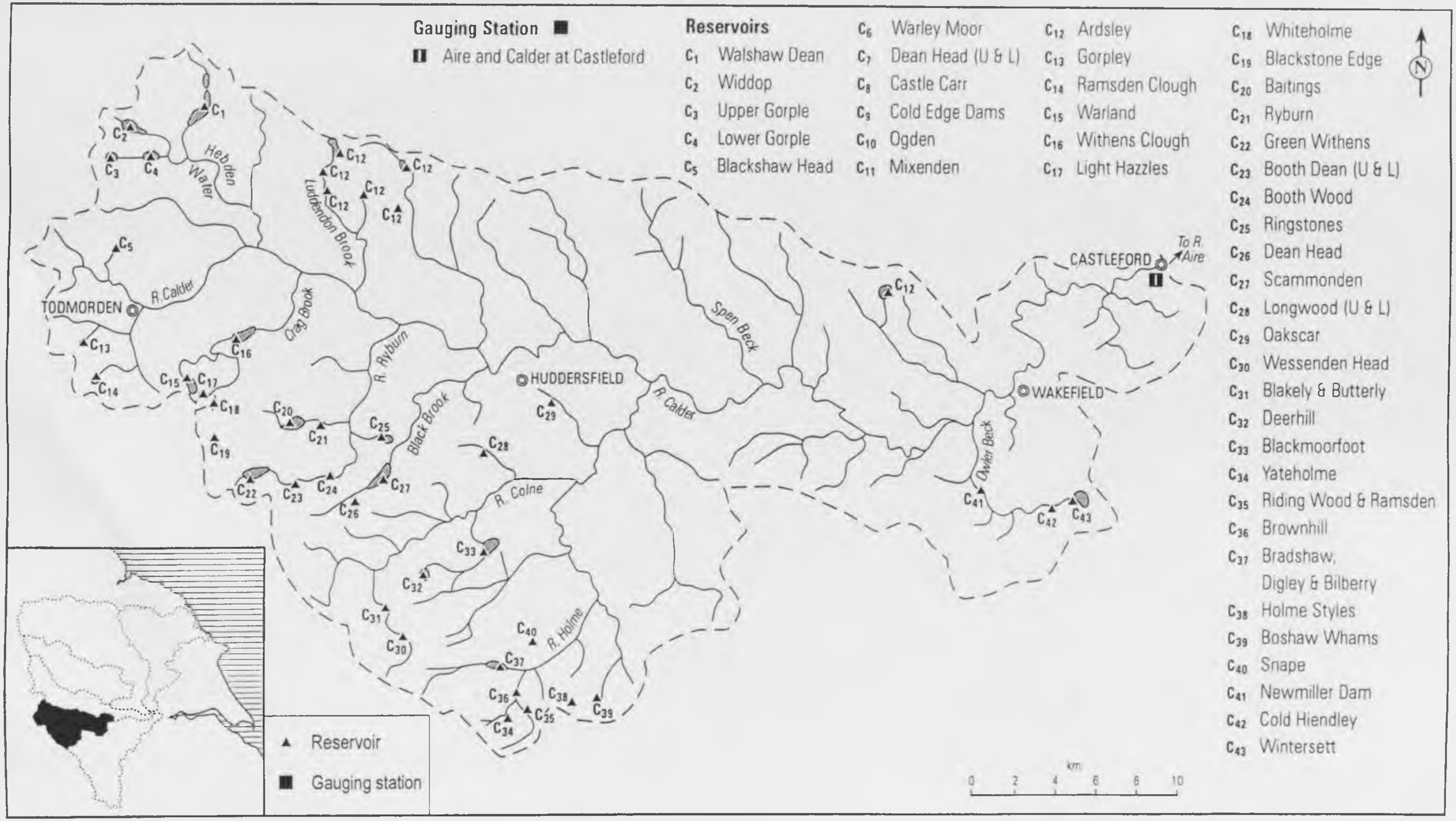
Appendix E(ii): *Reservoirs in the Nidd and Wharfe catchments*



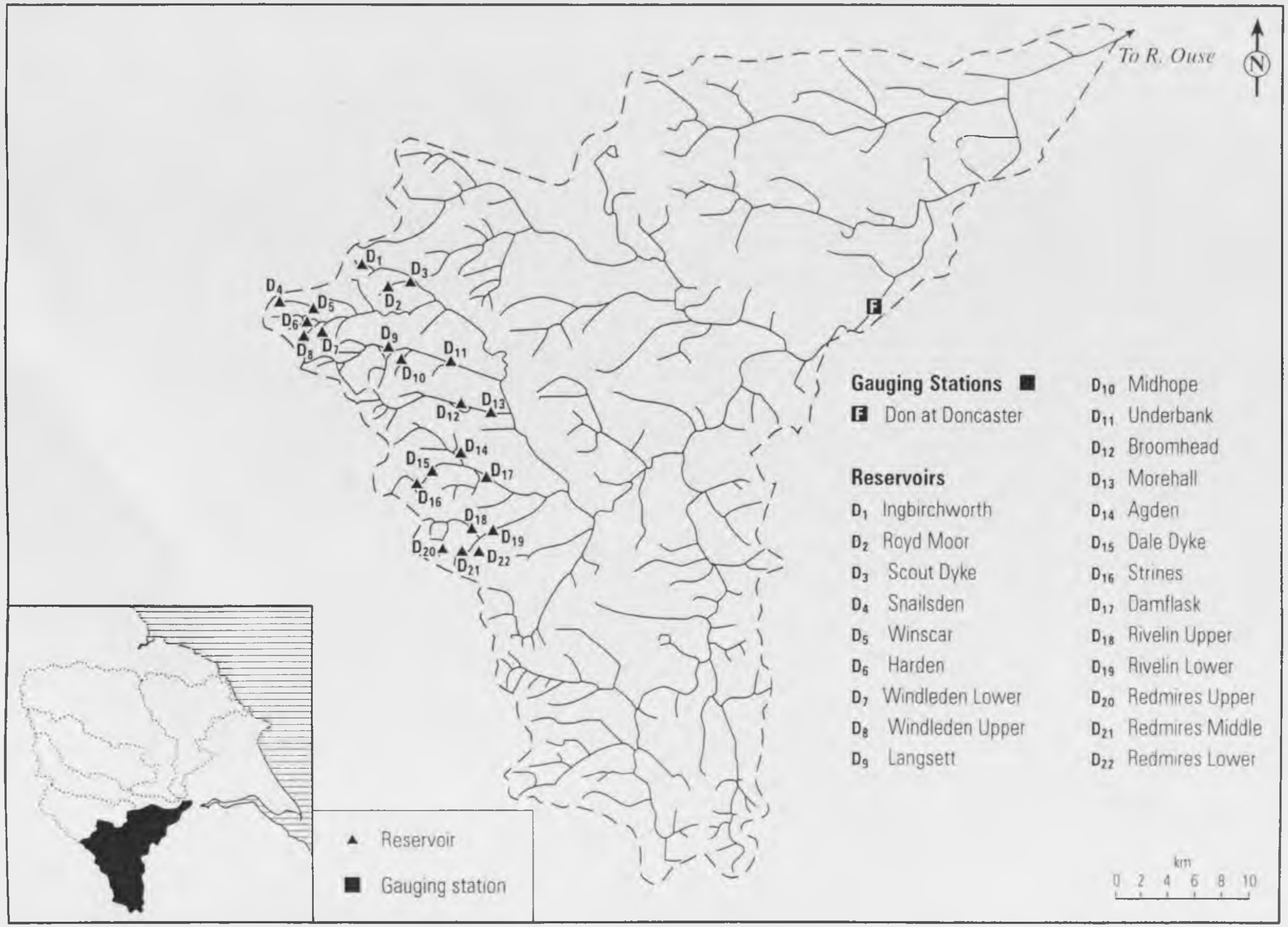
Appendix E (iii): *Reservoirs in the Aire catchment*



Appendix E (iv): Reservoirs in the Calder catchment



Appendix E(v): Reservoirs in the Don catchment



Appendix E(vi) : Summary tables of reservoirs in each catchment

Rivers Swale, Ure and Ouse Catchments

Name of Reservoir	N.G.R.	Year Built	Original Capacity (tcm)	Useable Capacity (tcm)	Compensation Required (tcmd)	Catchment Area (km^2)	Group	Code on Diagrams
Cod Beck	SE 463 986	1953	523	470	3.000	7.60	Swale	S_1
Oakdale Upper	SE 472 961	1914	58	54	0.000	2.59	Swale	S_2
Boltby	SE 497 885	1882	120	130	0.000	3.19	Swale	S_3
Leighton	SE 163 788	1929	4775	4955	0.000	22.88	Ure	U_1
Roundhill	SE 152 773	1916	2503	2446	13.661	12.43	Ure	U_2
Lumley Moor	SE 223 707	1888	353	381	0.455	2.34	Ure	U_3

Appendix E(vi) con't : Summary tables of reservoirs in each catchment

Rivers Nidd and Wharfe Catchments

Name of Reservoir	N.G.R.	Year Built	Original Capacity (tcm)	Useable Capacity (tcm)	Compensation Required (tcmd)	Catchment Area (km^2)	Group	Code on Diagrams
Angram	SE 040 760	1913	4736	4639	0.000	14.65	Nidd	N_1
Scar House	SE 058 769	1936	10064	9414	0.000	30.10	Nidd	N_2
Gouthwaite	SE 140 682	1901	7114	5811	20 to 614	50.87	Nidd	N_3
John O'Gaunts	SE 221 546	1890	113	110	0.000	n/a	Nidd	N_4
Beaverdyke	SE 228 546	1890	503	467	0.909	2.87	Nidd	N_5
Scargill	SE 233 535	1906	873	892	0.000	4.45	Nidd	N_6
Ten Acre	SE 248 534	1875	152	149	0.000	2.06	Nidd	N_7
Grimwith	SE 060 645	1984	21772	21764	river support	28.33	Wharfe	W1
Barden Upper	SE 012 578	1882	2114	1943	0.000	6.34	Wharfe	W2
Barden Lower	SE 035 567	1874	2291	2200	0.000	7.81	Wharfe	W3
Chelker	SE 055 515	1866	1036	982	0.000	5.22	Wharfe	W4
March Ghyll	SE 122 511	1906	395	409	0.636	3.93	Wharfe	W5
Thruscross	SE 152 578	1966	7842	7894	0.000	28.82	Washburn Valley	W6
Fewston	SE 187 541	1879	3846	3814	0.000	23.91	Washburn Valley	W7
Swinsty	SE 196 528	1876	3937	4655	0.000	16.28	Washburn Valley	W8
Lindley Wood	SE 215 493	1875	3045	2920	18.185	18.23	Washburn Valley	W9

Appendix E(vi) con't : Summary tables of reservoirs in each catchment

River Aire Catchment

Name of Reservoir	N.G.R.	Year Built	Original Capacity (tcm)	Useable Capacity (tcm)	Compensation Required (tcmd)	Catchment Area (km^2)	Group	Code on Diagrams
Elslack	SD 937 482	1932	232	223	0.000	1.86	Aire	A_1
Keighley Moor	SD 989 394	1846	332	347	0.682	1.57	Worth Valley	A_2
Watersheddles	SD 969 380	1878	864	839	0.000	6.47	Worth Valley	A_3
Ponden	SD 995 372	1877	964	891	0.500	3.49	Worth Valley	A_4
Lower Laithe	SE 013 368	1926	1314	1235	7.500	4.37	Worth Valley	A_5
Leeshaw	SE 016 353	1879	600	493	3.0/10.0	2.04	Worth Valley	A_6
Leeming	SE 038 344	1877	550	563	3.0/10.0	1.94	Worth Valley	A_7
Thornton Moor	SE 052 330	1885	795	702	0.000	5.12	Thornton Moor	A_8
Stubden	SE 062 332	1868	450	406	0.000	5.27	Thornton Moor	A_9
Hewenden	SE 074 356	1843	298	231	6.300	3.96	Thornton Moor	A_{10}
Doe Park	SE 078 343	1862	486	408	3.600	8.22	Thornton Moor	A_{11}
Embsay	SD 998 546	1907	798	723	1.186	2.95	Aire	A_{12}
Whinney Gill	SD 998 512	1876	209	168	0.000	0.75	Aire	A_{13}
Silsden	SE 045 477	1862	650	555	2.409	7.82	Aire	A_{14}
Sunnydale	SE 101 433	1862	31	27	Not in use	4.70		A_{15}
Graincliffe	SE 118 421	1885	500	443	0.000	4.53	Rombalds Moor	A_{16}
Eldwick	SE 122 413	1860	123	103	1.000	0.75	Rombalds Moor	A_{17}
Weecher	SE 136 421	1892	341	153	0.430	1.86	Rombalds Moor	A_{18}
Reva	SE 151 426	1894	545	496	0.791	2.91	Rombalds Moor	A_{19}

Appendix E(vi) con't : *Summary tables of reservoirs in each catchment*

River Calder Catchment

Name of Reservoir	N.G.R.	Year Built	Original Capacity (tcm)	Useable Capacity (tcm)	Compensation Required (tcmd)	Catchment Area (km^2)	Group	Code on Diagrams
Walshaw Dean-m	SD 966 335	1907	1111	1063	0.000	3.01	Hebden Group	C_1
Walshaw Dean-u	SD 968 345	1907	932	862	0.000	4.70	Hebden Group	C_1
Walshaw Dean-l	SD 960 330	1907	727	658	0.000	1.70	Hebden Group	C_1
Widdop	SD 930 330	1878	2912	2771	0.000	9.00	Hebden Group	C_2
Gorple Upper	SD 920 314	1934	1731	1716	0.000	3.82	Hebden Group	C_3
Gorple Lower	SD 940 314	1934	1261	1214	0.000	4.20	Hebden Group	C_4
Warley Moor	SE 030 317	1872	879	913	3.019	3.72	Luddenden	C_6
Dean Head Lower	SE 022 305	1872	286	276	0.000	0.17	Luddenden	C_7
Dean Head Upper	SE 022 308	1872	269	240	0.000	1.52	Luddenden	C_7
Ogden	SE 063 309	1858	1008	974	0.000	4.62	Hebble	C_{10}
Mixenden	SE 060 290	1873	482	451	0.000	0.77	Hebble	C_{11}
Gorpley	SD 910 230	1905	605	556	1.330	2.83	Hebden Group	C_{13}
Ramsden	SE 114 056	1892	394	324	0.000	3.07	Holmbridge	C14
Withens Clough	SD 984 230	1894	1364	1467	2.637	4.95	Ryburn	C_{16}
Baitings	SE 010 189	1958	3523	3307	6.819	13.37	Ryburn	C_{20}
Ryburn	SE 023 187	1933	1000	995	0.000	4.76	Ryburn	C_{21}
Green Withens	SD 990 163	1898	1387	1365	n/a	4.59	Rishworth	C_{22}
Boothwood	SE 030 163	1971	3637	3637	0.000	2.74	Rishworth	C_{24}
Ringstone	SE 050 180	1888	1068	991	0.000	5.77	Rishworth	C_{25}
Dean Head	SE 038 152	1840	454	438	0.000	2.02	Scammonden	C_{26}
Scammonden	SE 053 167	1970	7873	7420	15.600	20.90	Scammonden	C_{27}
Wessenden Head	SE 068 076	1881	378	359	0.000	3.26	Wessenden	C_{30}

(continued)

Appendix E(vi) con't : Summary tables of reservoirs in each catchment

River Calder Catchment (con't)

Name of Reservoir	N.G.R.	Year Built	Original Capacity (tcm)	Useable Capacity (tcm)	Compensation Required (tcmd)	Catchment Area (km^2)	Group	Code on Diagrams
Blakeley	SE 054 096	1903	364	137	0.000	3.92	Wessenden	C_{31}
Butterley	SE 047 105	1907	1832	1725	8.068	2.37	Wessenden	C_{31}
Deerhill	SE 070 117	1875	777	752	1.397	3.84	Wessenden	C_{32}
Blackmoorfoot	SE 099 130	1876	3204	2968	3.280	8.12	Wessenden	C_{33}
Yateholme	SE 112 047	1878	415	416	0.000	1.19	Holmbridge	C_{34}
Riding Wood	SE 116 052	1878	235	190	0.000	2.32	Holmbridge	C_{35}
Brownhill	SE 117 064	1928	1209	1243	6.819	3.02	Holmbridge	C_{36}
Bilberry	SE 103 070	1838	305	35	n/a	n/a	Holmbridge	C_{37}
Digley	SE 110 070	1953	3364	3443	6.564	1.46	Holmbridge	C_{37}
Holmestyes	SE 140056	1838	314	312	0.890	2.19	Holmbridge	C_{38}
Boshaw Whams	SE 153 057	1840	255	213	0.000	1.09	Holmbridge	C_{39}

Other Reservoirs (no data) : Castle Carr, Cold Edge Dams, Ardsley, Warland, Light Hazzles, Whitcholme, Blackstone Edge, Booth Dean, Longwood, Oakscar, Ramsden Wood, Bradshaw, Snape, New Miller Dam, Cold Hiendley, Wintersett

Appendix E(vi) con't : Summary tables of reservoirs in each catchment

River Don Catchment

Name of Reservoir	N.G.R.	Year Built	Original Capacity (tcm)	Useable Capacity (tcm)	Compensation Required (tcmd)	Catchment Area (km^2)	Group	Code on Diagrams
Ingbirchworth	SE 215 060	1868	1373	1229	0.045	7.72	Don	D_1
Royd Moor	SE 222 048	1934	877	851	0.000	4.53	Don	D_2
Scout Dyke	SE 235 047	1928	736	694	2.700	2.92	Don	D_3
Snailsden	SE 136 040	1899	196	165	0.000	0.85	Winscar	D_4
Winscar	SE 153 026	1975	8296	7590	0.000	7.10	Winscar	D_5
Harden	SE 153 037	1899	366	335	0.000	1.20	Winscar	D_6
Windleden Lower	SE 158 019	1872	376	343	0.000	0.78	Winscar	D_7
Windleden Upper	SE 153 013	1890	638	597	0.000	2.01	Winscar	D_8
Langsett	SE 214 002	1905	6401	5492	0.000	21.06	Little Don	D_9
Midhope	SK 223 994	1903	1859	1877	0.000	5.53	Little Don	D_{10}
Underbank	SK 253 992	1907	2955	2867	21.700	12.15	Little Don	D_{11}
Broomhead	SK 269 959	1934	5192	4937	0.000	21.96	Ewden	D_{12}
Morehall	SK 287 958	1930	2164	2173	12.000	4.33	Ewden	D_{13}
Agden	SK 261 923	1869	2859	2902	0.000	12.15	Loxley	D_{14}
Dale Dyke	SK 243 917	1875	2209	2049	0.000	4.41	Loxley	D_{15}
Strines	SK 232 905	1869	2332	1923	0.000	11.70	Loxley	D_{16}
Damflask	SK 284 907	1896	5264	5106	36.000	15.17	Loxley	D_{17}
Rivelin Upper	SK 271 868	1848	223	200	0.000	11.59	Rivelin	D_{18}
Rivelin Lower	SK 277 867	1848	796	616	0.000	18.05	Rivelin	D_{19}
Redmires Upper	SK 259 855	1854	1559	1382	0.000	8.86	Redmires	D_{20}
Redmires Middle	SK 264 855	1836	852	769	0.000	0.98	Redmires	D_{21}
Redmires Lower	SK 268 855	1849	634	628	0.000	0.57	Redmires	D_{22}