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River response to small climatic change: the Tyne Basin, N.E. England

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Abstract

This paper examines the timing, nature and magnitude of river response in upland, piedmont and lowland reaches of the Tyne, northern England, to high frequency (20-30 year) changes in climate and flood regime since 1700 AD. Over this period fluvial activity at all three sites has been characterised by alternating periods of river bed incision and stability that coincide with non-random, decadal-scale fluctuations in flood frequency and hydroclimate linked to changes in the configuration of large-scale upper atmospheric air masses. Episodes of widespread channel bed incision (1760-1799, 1875-1894, 1955-69) correspond with clustering of large floods (>20 year return period) and cool, wet climate under meridional circulation regimes. Phases of more moderate flooding (5-20 year return period), dominated by zonal circulation types (1820-1874, 1920-1954), are associated with channel-bed stability throughout the catchment, but with enhanced lateral reworking and sediment transfer in upper reaches of the catchment and channel narrowing and infilling downstream. Intervening periods (1800-19, 1895-1919) with "transitional" conditions (no dominant circulation regime) and low flood frequency are associated with reduced rates of fluvial activity. These findings have significant implications for the prediction of fluvial response to future climate changes.

Acknowledgements

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Introduction

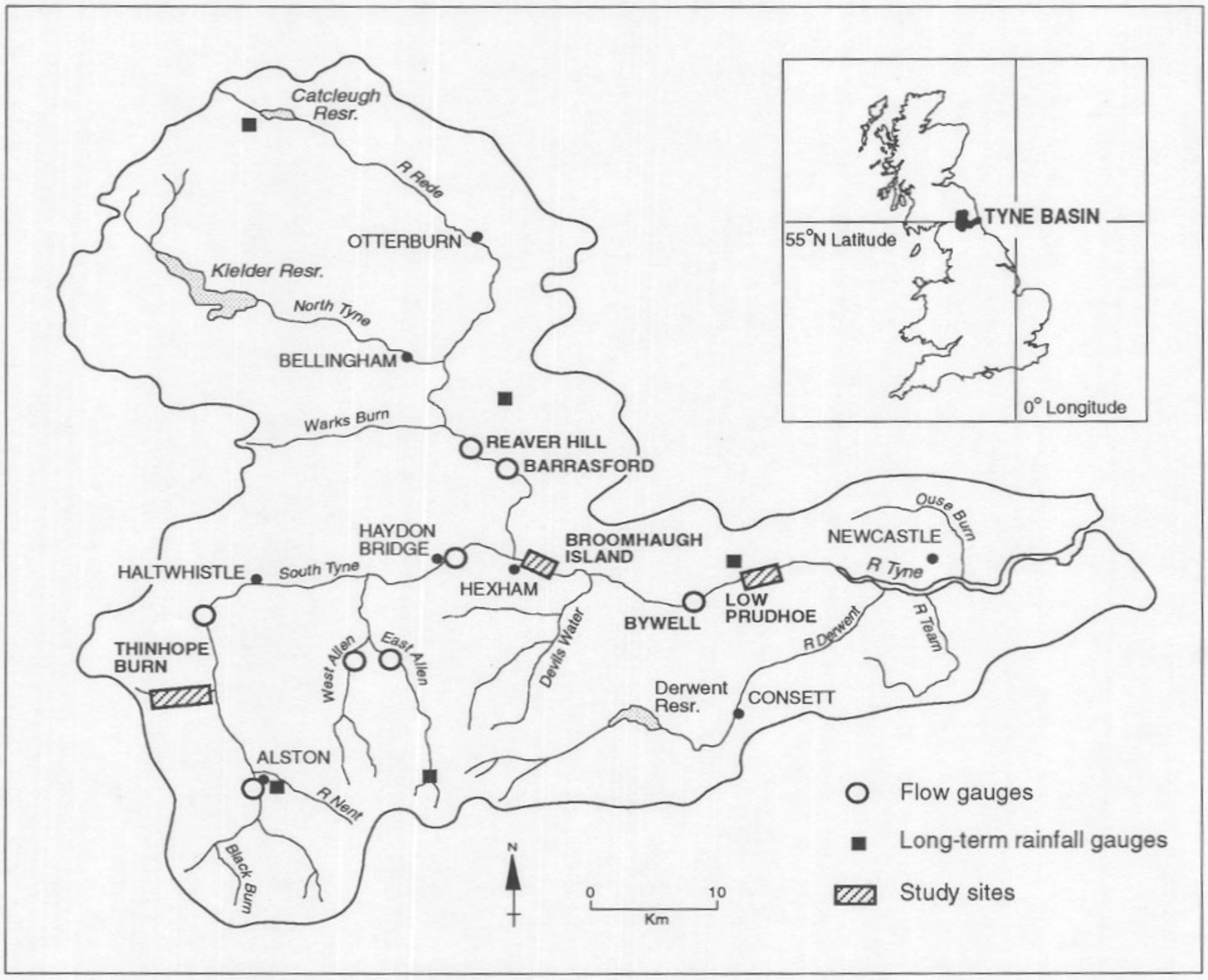
Understanding of the relationships between flood frequency and magnitude and channel and floodplain adjustment, at a river-basin scale, is fundamental for interpretation of Holocene alluvial sequences and assessment of the likely impact of future environmental changes on river systems. The influence of small to medium-scale variations in hydroclimate is particularly important, given the magnitude of climate changes predicted as a result of global warming over the next 40 years or so (Department of the Environment 1991, Macklin, Passmore & Rumsby 1992, Newson & Lewin 1991). However, while a number of studies in the USA (Balling & Wells 1990, Graf et al 1991, Hereford 1984, Knox 1984, Knox et al 1975) and Australia (Erskine & Bell 1982, Warner 1987) have demonstrated the sensitivity of river sediment systems to high frequency climate changes, to date there has been no equivalent work in a British watershed. In the UK, historical and longer-term investigations in both upland and lowland river basins have traditionally emphasised the impact of human activity. Many lowland studies have been based in small catchments (Brown & Barber 1985) or located in areas with a long history of intensive human occupation (Burrin 1985; Robinson & Lambrick 1984), factors likely to exaggerate human effects and make climatic causal links difficult to determine (Starkel 1983). A lack of sufficiently detailed hydroclimatic information has meant that studies even in less populated upland river basins in north and west Britain have tended to focus on anthropogenic impacts on river activity (e.g. Harvey et al 1981, Hooke et al 1990, Lewin et al 1983).

Recent investigations in the Tyne catchment, northern England have provided well-dated, high resolution reconstructions of channel and floodplain activity over the last 300 years or so (Macklin, Rumsby & Heap 1992, Macklin, Rumsby & Newson 1992, Rumsby 1991). The availability of comprehensive documentary and instrumental climate and flood records over the same period has provided an excellent opportunity to examine causal links between climate and river activity in some detail. This paper evaluates the timing, nature and magnitude of river response to decadal-scale changes in hydroclimate and flood regime since ca. 1700 AD at 3 reaches in upland, piedmont and lowland locations within the Tyne catchment. In contrast to previous investigations of historic river activity in upland Britain, which have concentrated on channel planform changes (e.g. McEwen 1989), this paper focuses on vertical channel response. The timescale of the study encompasses the latter stages of the Little Ice Age climatic deterioration and subsequent warming phase, and is therefore particularly appropriate in terms of providing a possible analogue for river response to future climate changes (cf. Newson & Lewin 1991).

Study area

The River Tyne (Figure 1) is a gravel-bed river with a drainage area of 2927 km^2. It is fed by two major tributaries; the River South Tyne (drainage area 800 km^2) which flows north off the Northern Pennines and the River North Tyne (drainage area 1118 km^2) which flows south from

Figure 1 Map of the Tyne catchment showing location of the study sites at Thinhope Burn, Broomhaugh Island and Low Prudhoe



the Bewcastle Fells and southern part of the Cheviot Hills. The catchment is underlain primarily by Carboniferous sandstones, limestones and shales, with outcrops of igneous rocks in the headwaters of the North Tyne (Cheviot granite) and lower reaches of the North and South Tyne (Whin Sill). Headwater tributaries of the South Tyne drain extensive areas of base-metal mineralisation, principally galena (PbS) and sphalerite (ZnS), associated with the Northern Pennine Orefield (Dunham 1990). Pleistocene glaciogenic sediments cover valley slopes and infill valley floors within the Tyne basin. In common with many river basins in northern and western Britain (e.g. Macklin & Lewin 1986, Hooke et al 1990), the Tyne has experienced net incision over the Holocene and present river channels are inset within glacial or fluvioglacial deposits, Holocene alluvium or bedrock.

High catchment relief (893 m) and relatively short channel length means that valley gradients throughout the system are steep (e.g. up to 0.2 m m^{-1} in headwater tributaries of the South Tyne, around 0.019 m m^{-1} in the middle Tyne and 0.001 m m^{-1} in the lower Tyne), allowing a rapid streamflow response to rainfall. Combined with high annual rainfall totals in the west (ca. 1750 mm a^{-1}) and north of the catchment (ca. 1250 mm a^{-1}) this results in high stream power throughout the system[1] and the potential for geomorphologically "effective" floods (Newson & Macklin 1990). Three reaches were chosen for detailed study (Figure 1) that have experienced marked vertical changes (channel bed incision, floodplain and channel sedimentation) during large floods over the past several hundred years, and have well-developed and well-dated alluvial sequences. The main characteristics of each site are briefly outlined below; detailed stratigraphies and river histories are given in Macklin, Rumsby & Heap (1992), Macklin, Rumsby & Newson (1992) and Rumsby (1991).

- (1) Thinhope Burn (Grid Reference NY 680550) is a steep (<0.01-0.1 m m^{-1}) and deeply incised stream that drains a small moorland catchment (12 km^2) on the north-west flank of the Northern Pennines and flows into the River South Tyne 9 km north west of Alston (Figure 1). Recent investigations (Macklin, Rumsby & Heap 1992) have revealed a striking transformation of channel and floodplain sedimentation styles in Thinhope in the late Holocene (post ca. 250-550 AD), with the replacement of a relatively stable meandering channel, and a floodplain accreting fine-grained sediment, by a vertically and laterally active, low sinuosity boulder bed stream with a high coarse sediment load. Channel and floodplain metamorphosis has been associated with unprecedented (viewed in the context of earlier Post-glacial valley floor development) rates of channel incision, punctuated by periods of relative stability and limited valley floor sedimentation. The most recent major phase of incision began in the early part of the eighteenth century and lichenometric dating of

[1] For example, unit stream power of 118 W m^{-2} was calculated for the August 1986 "Hurricane Charley" flood at Bywell (Grid Reference NZ 049613, in the lower Tyne valley (Rumsby, unpublished).

extensive cobble and boulder flood deposits that form prominent terraces, indicate more than 4 m of stream erosion (locally through bedrock) has occurred since ca. 1766.

•(2) Broomhaugh Island (Grid Reference NY 945643) is located in the middle Tyne valley near Hexham (Figure 1), 3 km downstream of the North and South Tyne confluence (gradient 0.019 m m^{-1}, catchment area 1918 km^2). Development of the island over last 300 years, documented using cartographic and aerial photograph evidence and trace-metal dating of fine-grained alluvial sediments (Rumsby 1991), has taken place through progressive trimming and streamlining upstream, and accretion of successive sediment units downstream. As a consequence of episodic river bed incision younger sediment units form a series of narrow, inset alluvial terraces wrapped round the downstream end of the island.

•(3) Low Prudhoe (Grid Reference NZ 088637) is located in the lower Tyne valley, 15 km west of Newcastle upon Tyne (Figure 1) (gradient 0.001 m m^{-1}, drainage area 2198 km^2). Over the last 130 years the river channel at Low Prudhoe has narrowed appreciably as the result of incision which elevated former lateral gravel bars above the level of the low flow channel and enabled them to be colonised by vegetation. High rates of fine-grained vertical accretion (up to 7 cm a^{-1}) at this site have allowed detailed preservation of flood-related bedding structures and units. Trace-metal dating of individual flood units, provide a detailed record of flood and river activity at Low Prudhoe since ca. 1890 (Macklin, Rumsby & Newson 1992).

Nature of climate, flood, land-use and alluvial records

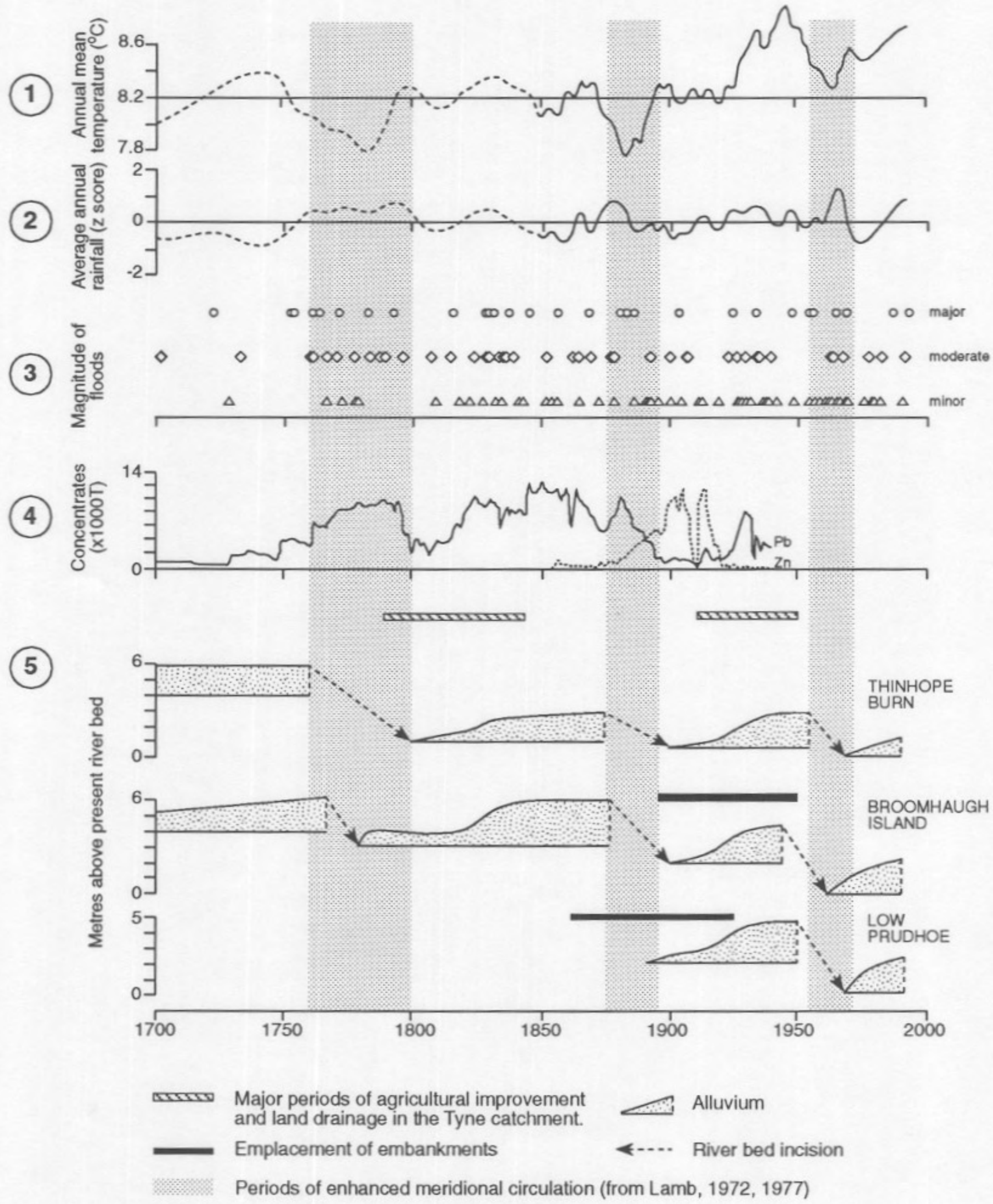
The main trends in hydroclimate (precipitation, temperature), flood frequency and magnitude, land-use and channel modification in the Tyne catchment since 1700 AD are plotted in Figure 2, along with the height number and thickness of dated alluvial units at Thinhope Burn, Broomhaugh Island and Low Prudhoe. The nature of the principal data sources are outlined below.

Climate

Instrumental records of precipitation and temperature are available for locations within the Tyne catchment since the mid-nineteenth century. Given that many long-term records have problems of non-stationarity associated with factors such as station relocation, changes in instrumentation and changes in surroundings, homogenised series were used where possible.[2] For earlier periods, information on climatic conditions in northern England can be obtained from a range of documentary sources, including diaries, scientific publications and parish registers (e.g. Brand 1789, Foggitt 1971, Fordyce 1877, Sykes 1866, Tufnell 1987, 1990). Additionally several proxy

[2] For example, Jones (1981) has produced an homogenous rainfall series for Allenheads (UK Grid Reference NY 860453; Figure 1) covering the period back to 1854.

Figure 2 Time-level diagram for alluvial units at Thinhope Burn, Broomhaugh Island and Low Prudhoe, 1700-1990. Major changes in flood regime, climate and land-use are also shown.



(1) Annual mean temperature. Post 1850 - Durham Observatory data (from Harris 1985); pre 1850 - generalised England and Wales data (Lamb 1977)

(2) Average annual precipitation. Post 1850 - data from Whittle Dene gauge in the lower Tyne valley (Jones, unpublished); pre 1850 - generalised data (Lamb 1977)

(3) Flood frequency and magnitude. Number of major, moderate and minor floods / year recorded in documentary sources. (Archer, unpublished; Jones *et al*, 1984)

(4) Production figures for heavy metal mining in the Tyne catchment (from Dunham, 1990)

(5) River activity at Thinhope Burn, Broomhaugh Island and Low Prudhoe, 1700-1900, showing periods of river bed incision and alluvial sedimentation

data are available (Lamb 1977), such as an index of wetness derived from recurrence surfaces in Bolton Fell Moss, Cumbria (Barber 1981). Mean annual precipitation and temperature data, such as those presented in Figure 2 provide a general indication of prevailing surface moisture budgets, but not the occurrence of extreme events.

Flood frequency and magnitude

The River Tyne is currently gauged at 8 sites (Figure 1), mainly located in middle and lower reaches of the catchment. The flood records provided by these gauges are relatively short (Figure 2); the first gauging station was emplaced in 1939, at Barrasford (Grid Reference NY 920733) on the North Tyne, although the majority date to the 1960s. Comprehensive documentary flood evidence, extends the River Tyne flood series back to 1700 AD (Archer 1987, Archer 1992, Jones et al 1984). Although the information provided in documentary sources varies in content and reliability, it is possible to make a qualitative assessment of flood magnitude based on criteria such as relative stage height, areal extent and duration of inundation, degree and nature of damage reported and emplacement of floodstones. This has allowed historical floods to be ranked and classified into major, moderate and minor events. Discharge estimates for 10 floods between 1766 and 1939, derived from flow competence calculations on boulder flood deposits in Thinhope Burn (Rumsby 1991), along with gauged flood discharges, allow approximate return periods to be assigned to each flood class: major floods have return periods in excess of 20 years, moderate floods are those with return periods between 5 and 20 years and minor floods, less than 5 years.

Land-use change and channel modifications

Most of the Tyne catchment is sparsely populated at present and consequently the channel is relatively unmanaged compared to many other British rivers. Population levels were higher in the past, with peaks during the seventeenth century in the North Tyne/Rede valleys (Harbottle & Newman 1977) and during the mid nineteenth century in the South Tyne valley (Wallace 1890). Three principal anthropogenic activities have affected the Tyne basin in the last ca. 300 years; heavy metal mining, agricultural improvement and direct channel modification.

Lead and zinc mining production in the catchment is well-documented (Dunham 1990, Hunt 1984, Raistrick & Jennings 1965). Large scale lead mining in a number of South Tyne tributary valleys (but not in Thinhope Burn), and in the lower South Tyne valley in the Haydon Bridge area (Figure 1) began around 1750 (Smith 1923). While mining operations had little direct impact on coarse sediment production, except very locally (Macklin 1986a), they had a more significant impact on suspended sediment yields through the input of fine-grained metalliferous waste (Macklin & Lewin 1989). In particular, deposition of zinc-rich sediment in riparian zones accelerated bank collapse by impairing vegetation growth.

Two main phases of land improvement and drainage, associated with agricultural expansion in the Tyne catchment, date to the early nineteenth century and between the First and Second

World Wars. The main effect of land drainage appears to have been to speed up runoff and enhance flood magnitudes downstream (cf. Higgs 1987). Direct channel modifications have been relatively limited in extent. Embankments and flood protection structures were constructed on an ad hoc basis in the nineteenth and early twentieth centuries in middle and lower reaches of the Tyne, including Broomhaugh Island and Low Prudhoe. These have reduced floodplain inundation, increased the magnitude of in-channel flows and may have enhanced subsequent incision at these sites. Impoundment of the upper River Rede (the major tributary of the North Tyne) by Catcleugh reservoir (Figure 1), completed in 1903, is unlikely to have modified trunk stream flow to any extent. The much larger Kielder reservoir (Figure 1), however, has reduced the magnitude of North Tyne flood peaks since its completion in 1983. Alluvial gravel extraction took place in several parts of the Tyne channel after the Second World War, ceasing in 1966 (Muir 1968). Aggregate was removed from the channel immediately upstream of Low Prudhoe in the 1950s and 1960s and probably accentuated incision at the site, however, neither of the other study reaches was directly affected by gravel extraction.

Alluvial record dating control

Fine-grained vertically accreted alluvium at Broomhaugh Island and Low Prudhoe were dated using trace metal chemistry (Macklin, Rumsby & Newson 1992, Rumsby 1991). The ages of coarse-grained cobble-boulder flood deposits in Thinhope Burn were determined by lichenometry (Macklin, Rumsby & Heap 1992). Map and aerial photographic evidence was also used to provide age brackets for alluvial units at all three reaches.

Recent river erosion and sedimentation histories in the Tyne catchment

The episodic nature of fluvial activity in the Tyne catchment over the last 290 years can be seen in Figure 2; with decadal fluctuations in channel vertical tendency and sedimentation evident at each of the study reaches. The major secular trends in river behaviour are outlined below.

1700-1799

Following one of the severest parts of the Little Ice Age in the seventeenth century (Lamb 1982), there was a progressive rise in temperature throughout the first half of the eighteenth century with low to moderate annual precipitation amounts (Lamb 1977) and a low frequency of flooding in the Tyne basin. Rates of fluvial activity in the Tyne catchment during this period appear to have been low with limited channel bed incision in Thinhope Burn, and river bed stability and vertical accretion of fine-grained sediment at Broomhaugh Island and Low Prudhoe. Several consecutive severe winters in the 1760s, however, marked the beginning of a general deterioration of climate lasting until the end of the century (Lamb 1977). This appears to have been a period of precipitation extremes, with both very dry (e.g. January-April 1779, March 1781, December 1783-September 1786) and very wet (e.g. January 1768-December 1770, November 1771-October 1774, July-October 1799) intervals (Wigley et al 1984). The latter are reflected in the Tyne flood record by an increase in flood frequency and magnitude (4 events with estimated return periods in excess of 100 years occurred during this time; Rumsby 1991). This appears to have been a phase of widespread channel trenching in the Tyne basin with up to 4 m of stream bed erosion in Thinhope Burn (Macklin, Rumsby & Heap 1992) and around 1 m at Broomhaugh Island (Rumsby 1991). Although the Low Prudhoe sedimentary record does not extend back to this period, an episode of channel incision in the lower Tyne valley dating to the late eighteenth century has been documented nearby at Farnley Haughs (Grid Reference NZ 004633; Macklin, Passmore & Rumsby 1992).

1800-1899

There was a gradual rise in summer and winter temperatures between ca. 1815 and 1870 with lower annual precipitation totals. Between 1820 and 1840, however, there was a phase of enhanced rainfall and moderate-sized floods (5-20 year return periods). All three study reaches seem to have experienced little vertical change in this period. Flooding in the 1820s and 1830s resulted in lateral reworking and limited aggradation of coarse sediment in Thinhope Burn (Macklin, Rumsby & Heap 1992), and accretion of fine-grained sediment in the middle and lower Tyne (Rumsby 1991). The last 20-30 years of the nineteenth century were characterised by lower annual mean temperatures and higher rainfall than the preceding decades (Harris, 1985) and a high frequency of major floods (>20 year return period). Channel trenching is evident in lower reaches of Thinhope Burn and at both the downstream study reaches (although on a more limited scale than in the late eighteenth century). Incision at Low Prudhoe had largely ceased by 1890, but continued until the turn of the century at Broomhaugh Island and Thinhope Burn.

1900-1992

A warming trend continued from the end of the nineteenth century until the late 1930s with temperatures peaking around 1940 in northern England (Harris 1985). Enhanced evapotranspiration, associated with the warmer conditions, resulted in lower runoff and smaller floods for a given magnitude of precipitation event; medium-size floods in the 1920s were associated with high annual rainfall totals. Low rates of fluvial activity prevailed between 1900 and 1920, however, the 1920s and 1930s were characterised by high rates of fluvial activity and significant transfer of sediment. Aggradation of coarse flood deposits in Thinhope Burn followed lateral reworking and destabilisation of valley-sides. While at Broomhaugh Island and Low Prudhoe, rapid vertical accretion (up to 7 cm a^{-1} at Low Prudhoe and 8.3 cm a^{-1} at Broomhaugh Island) of fine-grained sediments took place within entrenched channels.

Low annual precipitation totals were recorded between 1940-1954 and relatively few floods (one major exception being a large event in 1947), corresponding with a phase of subdued river activity in the Tyne basin. There was a significant cooling trend throughout the 1950s and 1960s (Harris 1985), many years with above average annual rainfall totals and increased frequency of large magnitude floods (Figure 2). River bed erosion occurred at all three sites during this period, but was particularly marked in the middle and lower Tyne, with up to 3m of incision at Broomhaugh Island and Low Prudhoe. Initiation of incision appears to have been diachronous, beginning earlier in Thinhope Burn and Broomhaugh Island than Low Prudhoe.

Although mean annual temperatures have risen slightly since the late 1960s in north east England (Harris 1985), they are still generally lower than the 1920s-1940s levels. A decline in annual precipitation totals, frequency of flooding and size of flood peaks in the 1970s (Archer 1981) corresponded with low rates of fluvial activity in Thinhope Burn, where only two flood units, dating to 1972 and 1977, are evident. At Broomhaugh Island and Low Prudhoe river narrowing took place through accretion of fine-grained sediment within the channel. The last 10 years, however, have seen an increase in flooding in the Tyne catchment, with significant events recorded in August 1986 (30 year return period), December 1990, February 1991, December 1991 and March 1992. These have resulted in major bank erosion and channel widening at Broomhaugh and Low Prudhoe, but little change in Thinhope Burn.

Summary

Since 1700 AD fluvial activity at all 3 study sites has been characterised by periods of river bed incision or sedimentation that appear to coincide with non-random decadal-scale fluctuations in flood frequency and hydroclimate. Distinct clustering of large floods dating to around 1760-1790, 1875-1895 and 1955-1970 resulted in channel trenching. Intervening periods with higher mean annual temperatures, lower rainfall totals and fewer exceptional floods were associated with channel bed stability and floodplain rebuilding, but with significant spatial variation. Land-use activities in the Tyne catchment over the last 300 years or so (metal mining operations, agricultural improvement) appear to have had little effect on river behaviour, although direct channel modifications (construction of embankments, alluvial gravel extraction) probably accentuated incision in the middle and lower Tyne. These changes, however, have not influenced the temporal distribution of flood events; their impact appears to have been one of increasing the sensitivity of the Tyne to small-scale climate changes and reinforcing the climate signal.

Controls of high frequency climate change

The duration, intensity, distribution and type (rain, snow) of precipitation over an area are determined both by its geographical location (especially in relation to orographic features) and by the characteristics (moisture content, trajectory) of prevailing regional airflow types (Gregory et al 1991, Sweeny & O'Hare 1992). In mid latitudes, the position, direction and strength of regional weather systems are determined by the configuration large scale circumpolar airwaves in the upper atmosphere (Hirshboeck 1987). It has been suggested that short-term fluctuations in the configuration of upper atmospheric circulation patterns is a possible causal mechanism for high frequency hydroclimatic changes, such as those identified in the Tyne catchment (Knox et al 1975, Knox 1984, Hirschboeck 1987, Brakenridge 1980).

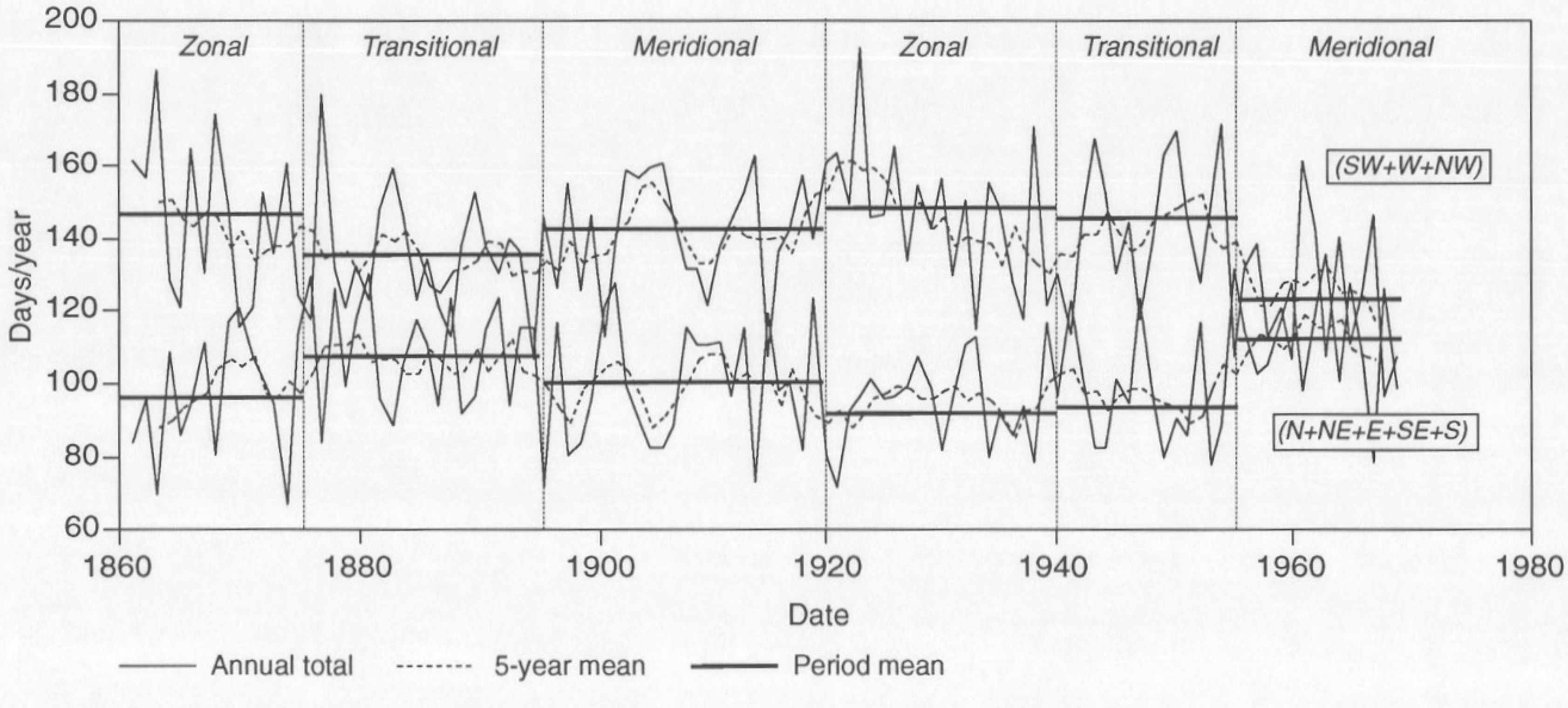
Circumpolar upper air waves in the northern hemisphere tends to alternate between two specific forms, zonal and meridional (Charney & DeVore 1979, Dzerdzeevskii 1968, Hirschboeck 1988, Kutzbach 1970, Knox et al 1975, Lamb 1977). While the precise mechanisms for these changes are not known in detail (Ford 1982), temperature appears to be the major control of the strength, pattern and position of circumpolar flow (Lamb 1982). Under warmer conditions flow is strongly zonal (west to east) with low amplitude, widely spaced waves. In cooler periods the lateral temperature gradient is steepened favouring more frequent and enhanced occurrences of north/south (meridional) and easterly wind patterns in mid latitudes. In addition, the main air streams are displaced southward, with increased amplitude and number of meanders in the circumpolar vortex.

Meteorological observations have allowed the timing of changes between these 2 upper atmospheric circulation configurations to be established for the last 100 years or so, with major break points identified around 1895, 1920 and 1950 (e.g. Dzerdzeevskii 1968; Knox et al 1975). Figure 3 plots yearly frequencies (total number of days) of zonal (west, southwest, northwest) and meridional (north, south, east, northeast, southeast) circulation patterns are plotted for the period 1861-1969, using a register of daily weather types assembled by Lamb (1972). The stepped nature of circulation changes is clear and, in addition to those identified above, significant break points are apparent at around 1875 and 1970. Higher frequencies of meridional types seem to have prevailed between 1875-1894 and 1955-1969, while zonal conditions were dominant between 1861-1874 and 1919-1954. The period 1895-1919 appears to have been "transitional" in character, with frequencies of zonal and meridional weather types close to the long-term mean. In the last 10 years (not shown), frequencies of zonal and meridional types have been low and there has been an increase in non-directional synoptic (pure cyclonic and anticylonic) weather systems (Briffa et al 1990).

Although systematic climate data is not available for the period before 1861, the principal features of the prevailing large scale upper atmosphere circulation have been inferred from proxy temperature and precipitation records (Lamb 1977, 1982). During the Little Ice Age (especially the period between 1600-1800 AD) climate zones in the Northern hemisphere shifted southwards towards the equator (Lamb 1982) and high amplitude waves in the circumpolar vortex pushed polar air masses over Britain, resulting in higher frequency of northerly (meridional) weather systems. Meridional circulation patterns appear to have been particularly strong in the mid-late eighteenth century, with a corresponding 22% reduction in the strength of mid-winter zonal circulation over the British Isles (Kington 1976).

Break points identified within the atmospheric circulation data correspond to significant changes in flood regime on the River Tyne (Table 1). Increased frequency of major floods (>20 year return period) is evident in meridional periods while more moderate floods (5-20 year return period) are found in zonal periods. Transitional phases appear to be characterised by low flood frequency. Two important synoptic characteristics associated with meridional configurations of the upper atmosphere favour large floods. First, high amplitude waves in the

Figure 3 Yearly frequencies (number of days/year) of zonal (southwesterly, northwesterly) and meridional (north, northeast, east, southeast, south) weather systems over Britain, 1861-1969 (data from Lamb, 1972). Mean frequencies for selected periods are also shown.



circumpolar vortex are liable to create stationary blocking situations which can lead to exceptional (high intensity, multiple peak) rainfall events (Rodda 1970, Hirschboeck 1987). Second, low temperatures and the prevalence of northerly/polar air masses result in low rates of evapotranspiration and higher soil wetness, as well as increased occurrence of snow, all of which promote rapid runoff and large flood peaks. In addition, the Tyne catchment, located to the east of the Pennines, the major rainfall divide in northern England (Wheeler 1990, Wigley et al 1984), is in the rain shadow of zonal weather systems travelling west to east, thus meridional systems, especially those from the north and northeast that have picked up moisture over the North Sea, are more important in terms of precipitation extremes over the area (Table 2).

Table 1 Comparison of total number of documented floods and number of major floods in the Tyne basin for different climate periods, 1700-1990

Time Period	Climate Regime	Total Number of Documented Floods	Mean Number of Documented Floods/Year[1]	Total Number of Major[2] Floods	Mean Number of Major[2] Floods/Year[1]
1700-1759	Transitional	6	0.10	1	0.02
1760-1799	Meridional	18	**0.46**	5	**0.13**
1800-1819	Transitional	5	0.26	1	0.05
1820-1874	Zonal	30	**0.55**	2	0.05
1875-1894	Meridional	12	**0.63**	3	**0.16**
1895-1919	Transitional	10	0.42	1	0.04
1920-1954	Zonal	21	**0.62**	3	**0.09**
1955-1969	Meridional	16	**1.14**	3	**0.21**
1970-1979	?	5	**0.55**	0	0
1980-1992	Meridional	4	0.33	1	0.05

[1] Emboldened figures represent values above the mean for the combined data set:
mean number of floods/year = 127/292 = 0.43;
mean number major floods/year = 20/292 = 0.07.
[2] Using the 20 largest floods as shown in Figure 2

Given that upper atmospheric air masses are hemispheric in extent, there should be some correspondence in the timing of changes in fluvial activity over significant areas of the globe. Table 3 compares trends in hydroclimate, flood frequency and fluvial activity in a number of river catchments in Europe, the USA and Australia. While the precise nature of river response and direction of channel change differs in each drainage basin, it is clear that the timing of major changes in regime are very similar, with major break points around 1900, 1940, 1950 and 1970, corresponding to those identified in this paper.

Table 2 Mean daily precipitation over the Tyne basin for different weather types in the Lamb (1972) classification (1952-1992)

Lamb (1972) classification category	Mean daily precipitation: Tyne Basin (mm)[1]	Mean daily precipitation: UK mean (mm)[1]
Anticyclonic	0.5	0.8
Cyclonic	**4.5**	**4.2**
Westerly	2.0	**3.6**
Northwesterly	1.0	1.6
Northerly	1.5	1.2
Northeasterly	1.7	1.0
Easterly	1.6	1.8
Southeasterly	2.0	3.4
Southerly	2.7	**4.2**
Southwesterly	3.0	2.6
Unclassified	2.2	3.2
Anticyclonic Westerly	1.5	1.6
Anticyclonic Northwesterly	0.5	0.5
Anticyclonic Northerly	0.5	0.4
Anticyclonic Northeasterly	0.5	0.4
Anticyclonic Easterly	0.5	0.6
Anticyclonic Southeasterly	0.5	1.4
Anticyclonic Southerly	0.5	1.9
Anticyclonic Southwesterly	1.0	2.1
Cyclonic Westerly	3.0	**4.0**
Cyclonic Northwesterly	2.2	2.1
Cyclonic Northerly	**4.0**	2.0
Cyclonic Northeasterly	**5.0**	2.2
Cyclonic Easterly	**3.5**	1.1
Cyclonic Southeasterly	3.0	**4.3**
Cyclonic Southerly	3.0	**4.7**
Cyclonic Southwesterly	**4.0**	**4.9**

[1] From Sweeny and O'Hare (1992). Emboldened figures represent values greater than one standard deviation above the mean.

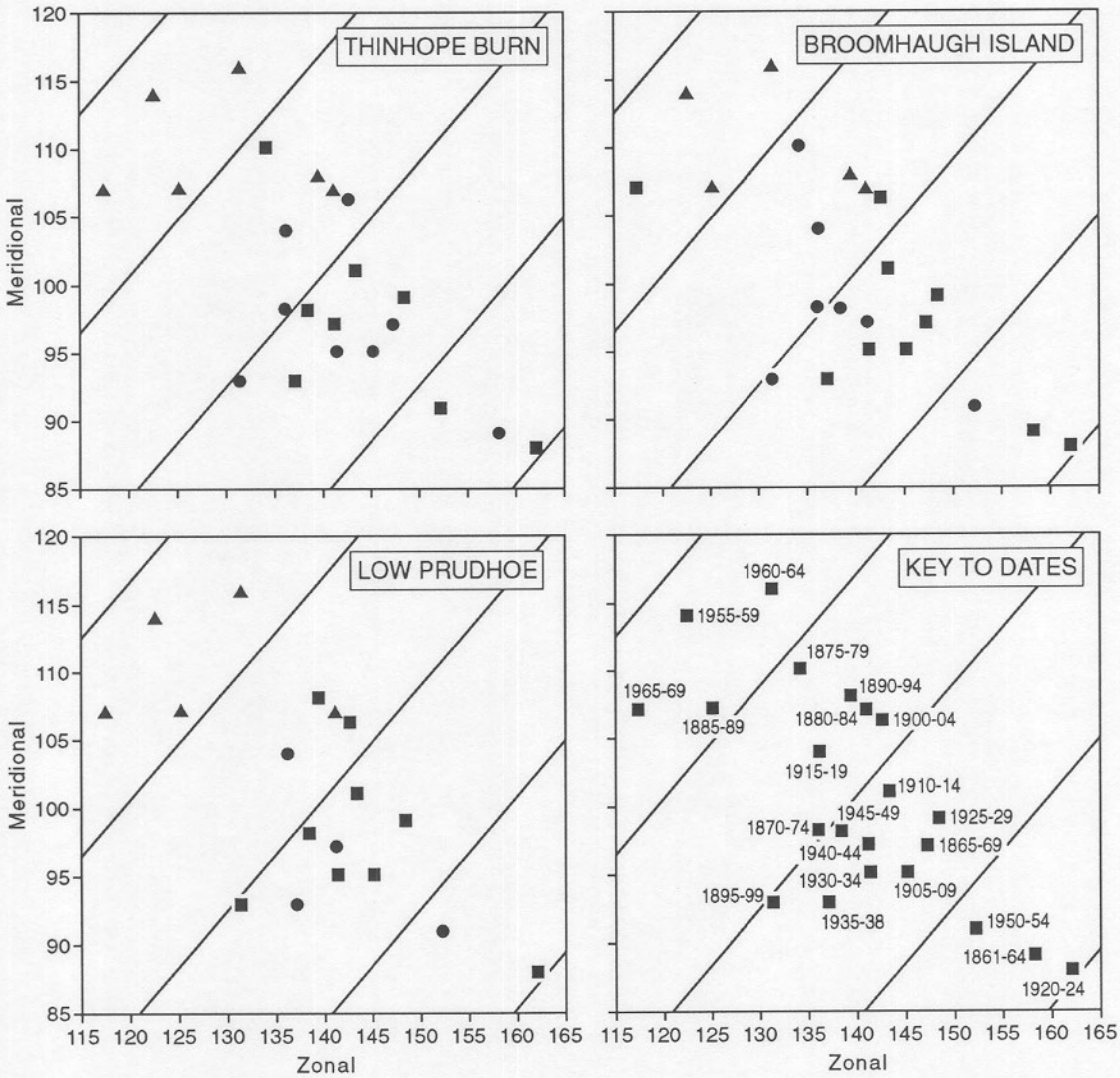
Channel and floodplain response to high frequency climate change

In Figure 4 trends in fluvial behaviour at Thinhope, Broomhaugh Island and Low Prudhoe are plotted together with prevailing circulation characteristics (average number of days/year classed as zonal and meridional) for five year periods between 1861 and 1969. Dividing lines on the graphs represent intervals of 0.5 standard deviation from the long-term mean annual number of days of each weather type. While there are important differences between the 3 reaches, discussed in detail below, some general patterns are apparent (Figure 5). Periods of pronounced

Table 3 Trends in hydroclimate, flood regime and river activity for selected river basins in Europe, North America and Australia

River basin	Area (km^2)	Time period of study	Break point	Hydroclimatic regime	Fluvial activity	Author
Mississippi, Minnesota, USA		1867-1981		Cool & moist, incr flood frequency & magnitude		Knox 1984
			1895	Warmer, decr flood magnitude		
			1940	Cool & moist, incr flood frequency & magnitude		
Little Colorado, Arizona, USA	44,000	1880-1984		Low flood frequency & magnitude	Floodplain alluviation	Hereford 1984
			1900	Cool & moist, incr flood frequency & magnitude	Erosion & incision	
			1942	Decr flood frequency & magnitude	Floodplain vertical accretion	
Pariah, Utah, USA	3,650	1923-1986		Larger & more frequent floods	Erosion, high suspended sediment yields	Graf et al 1991
			1942	Decr flood frequency & magnitude	Floodplain sedimentation, lower suspended sediment yields	
Zuni, New Mexico, USA	20-500	1895-1985		Low flood frequency & magnitude	Arroyo stability	Balling and Wells 1990
			1905	Increased flood frequency & magnitude	Arroyo cutting	
			1920	Low flood frequency & magnitude	Arroyo infilling	
			1970	Increased flood frequency & magnitude	Arroyo floor incision	
Upper Hunter, NSW, Australia		1900-1982		Low flood frequency & magnitude	Erosion of bed & banks, decr sinuosity	Erskine and Bell 1982
			1946	Incr flood frequency & magnitude		
Hawkesbury-Nepean, NSW, Australia	13,000	1799-1978		Flood dominated regime	Erosion, incr channel capacity	Warner 1987
			1820	Drought dominated regime	Narrowing & infilling,decr channel capacity	
			1864	Flood dominated regime	Erosion, incr channel capacity	
			1900	Drought dominated regime	Narrowing & infilling, decr channel capacity	
			1949	Flood dominated regime	Erosion, incr channel capacity	
Several major European rivers	44-578,000	1800-1989		Decreased runoff		Probst 1989
			1910	Increased runoff		
			1940	Decreased runoff		
			1950	Increased runoff		
			1970	Decreased runoff		

Figure 4 Plots of atmospheric circulation indicies for 5 year periods from 1861 to 1969 showing channel and floodplain activity at Thinhope Burn, Broomhaugh Island and Low Prudhoe.

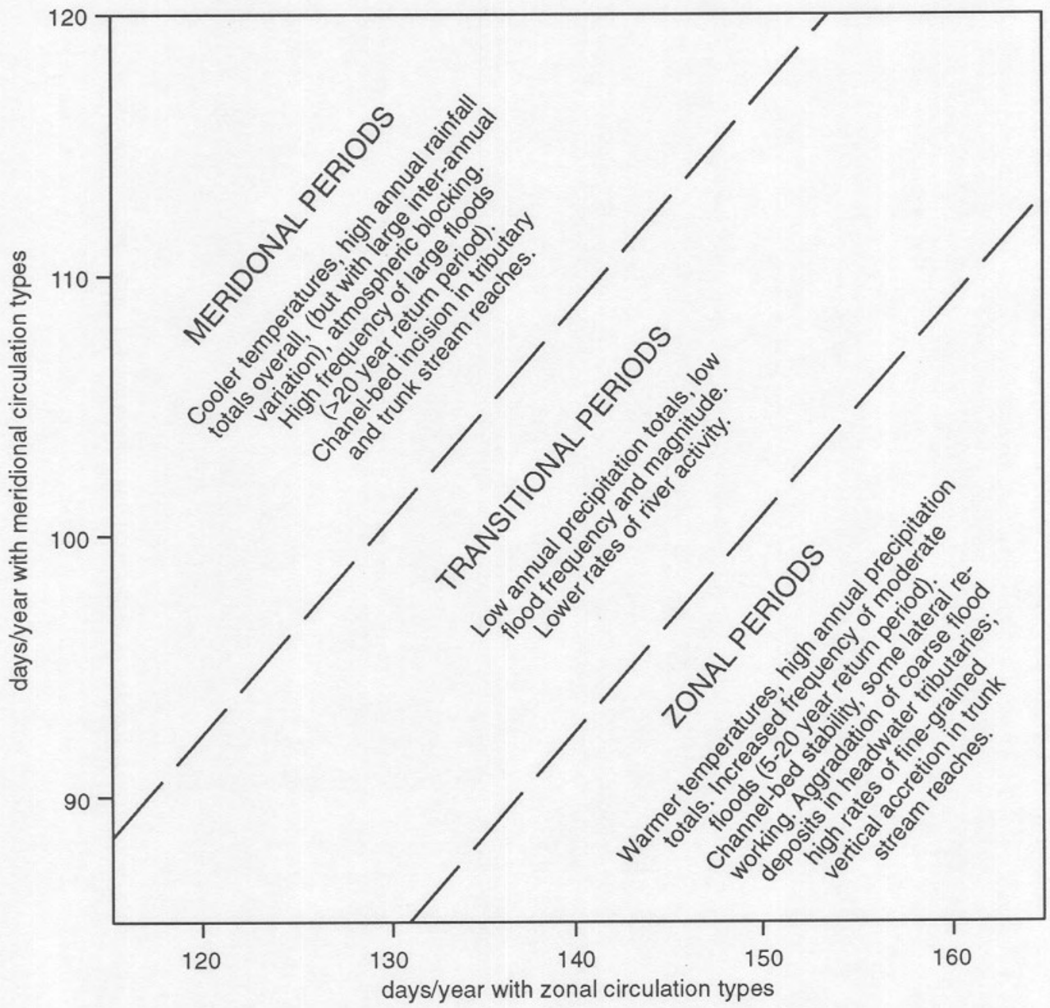


▲ Channel bed incision

● Channel bed stability
–aggradation of coarse-grained flood deposits (Thinhope Burn)
–high rates of vertical accretion (Broomhaugh Island and Low Prudhoe)

■ Low rates of river activity

Figure 5 Summary diagram showing response of the River Tyne during different climate regimes, 1861-1969.



channel incision have the highest number of days with meridional weather types, while episodes of lateral re-working and sedimentation in the River Tyne tend to occur during periods with a high proportion of zonal days. Transitional phases (with zonal and meridional frequencies close to the long-term mean) correspond with lower rates of fluvial activity.

Meridional periods

Since ca. 1750 AD the greater frequency of high magnitude floods during meridional periods has resulted in relatively rapid and widespread channel trenching in both headwater tributaries and trunk stream reaches of the Tyne. In detail, however, significant spatial variations in the precise timing and magnitude of river bed incision are apparent. In the mid-late eighteenth century incision appears to have started earlier, and was more marked in Thinhope Burn than at Broomhaugh Island and Low Prudhoe. Phases of incision in the late nineteenth century and mid twentieth century, however, show the opposite trend with the most pronounced erosion in the middle and lower Tyne. Two factors provide possible explanations for this. First, variations in the location, seasonality and nature of floods. Two floods, July 1766 and June 1777, that were the result of intense, localised but short-lived, summer storms that moved rapidly across the South Tyne catchment (Archer 1992), had a large impact in small catchments such as Thinhope Burn (Macklin, Rumsby & Heap 1992), resulting in marked incision but evoking little downstream response. In contrast, catchment-wide incision during the 1780s, 1875-1895 and 1955-1970 was associated with a preponderance of autumn and winter events, prolonged by snow melt augmentation of flood peaks (Archer 1992). Second, a reduction in floodwater storage in headwater tributaries following entrenchment in the late eighteenth century would have increased rates of runoff to the main channel, enhancing effective stream power thereby promoting incision in middle and lower reaches of the Tyne. Once incision had been initiated at reaches such as Broomhaugh and Low Prudhoe a number of factors favoured bed erosion; large upstream drainage areas and associated discharges, narrow channels, and relatively resistant, silty-sandy channel banks.

Zonal periods

In contrast to meridional periods the timing and nature of fluvial adjustments during zonal phases appears to have been more variable with appreciable differences in channel behaviour in upper and lower reaches of the Tyne related to sediment supply, calibre and quality. In Thinhope Burn, moderate flooding (5-20 year return period) under predominantly westerly weather types in the early to mid nineteenth century resulted in reworking and redistribution of sediment eroded at the end of the previous century and local aggradation (Macklin, Rumsby & Heap 1992). Flood events during the 1920s and 1930s, however, were associated with high rates of lateral reworking in the Thinhope Burn catchment with slope-channel coupling and input of fresh coarse sediment from valley sides (Macklin, Rumsby & Heap 1992). A wide range of flows are capable of transporting fine-grained sediment that constitutes vertical accretion units at Broomhaugh Island and Low Prudhoe. Flooding under zonal conditions between 1820-39 and

1920-39, enhanced bank erosion and lateral reworking in the upper Tyne released large quantities of fine sediment which resulted in exceptionally high rates of within-channel deposition in the middle and lower reaches of the catchment (Macklin, Rumsby & Newson 1992, Rumsby 1991).

Transitional periods

Transitional periods have generally been characterised by lower frequency of flooding and low rates of fluvial activity, particularly in headwater catchments. For example, while a range of sub-bankfull flows in the period 1895-1919 enabled within-channel vertical accretion at Broomhaugh Island and Low Prudhoe to continue, only one coarse flood unit (dating to 1912) was deposited in Thinhope Burn.

Response of the River Tyne to future climatic changes

Given the marked channel and floodplain adjustments in the Tyne basin over the last 300 years to high frequency climate change it is likely that it will be equally responsive to future changes predicted as the result of global warming. Notwithstanding the unreliability of GCMs for predicting regional climatic changes, several recent studies have postulated an increase in winter runoff totals over north-east England (Arnell 1992, Houghton et al 1990, Palutikof 1987), and others highlight an increase in the variability of precipitation over the UK both in space and time (Jones pers comm, Mayes 1992). It is possible that, given the past relationship between warmer temperatures and high zonality over north east England, moderate (5-20 year return period) rather than high (>20 year return period) magnitude floods will predominate in the Tyne basin leading to a period of channel infilling and floodplain reworking. Whilst recent incision of the main trunk channel has reduced the risk of severe overbank flooding, infilling would reduce channel capacity and hence increase the flood hazard. An alternative view, however, is that global warming will result in a reduction in the equator-pole thermal gradient and a continued decline in westerly (zonal) circulation (Sweeny and O'Hare 1992). Under this scenario, increased frequency of high magnitude floods in the Tyne basin woul lead to widespread channel bed incision. In either case, higher rates of bank erosion and reworking of mining-age sediment would re-introduce large quantities of metal contaminated sediment into the system that could have serious environmental and ecological consequences (cf. Macklin & Klimek 1992).

Conclusions

Over the last 290 years three river reaches in upland, piedmont and lowland locations of the Tyne catchment, northern England, have experienced marked channel and floodplain adjustments in response to relatively short-term (10-30 year) shifts in hydroclimate, which appear to be in phase with fluctuations in the configuration of the upper atmosphere. Widespread channel degradation phases in headwater tributaries and main channel reaches (identified by lateral discontinuities in river sequences, inset alluvial fills, unconformable contacts, terrace edges) are associated with an increase in the frequency and magnitude of flooding (>20 year return period) during cooler and wetter phases with a high frequency of meridional weather types. Whereas episodes of accumulation of fine sediment in main channel reaches, and high rates of lateral reworking further upstream, appear to be associated with increased frequency of moderate (5-20 year) floods, high wetness and relatively warm temperatures, under strongly zonal circulation regimes. Periods of relatively low fluvial activity are characterised by low moisture availability and low flood frequency, associated with transitional circulation regimes (moderate frequencies of both zonal and meridional weather types).

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