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Trends in flood seasonality of the River Ouse (Northern England) from archive and instrumental sources since AD 1600

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Abstract The last decade has witnessed an increase in the application of historical records (historical and documentary) in developing a more complete understanding of high-magnitude flood frequency; but little consideration has been given to the additional information that documentary accounts contain, particularly relating to flood seasonality. This paper examines the methods and approaches available in long-term flood seasonality analysis and applies them to the River Ouse (Yorkshire) in Northern England since AD 1600. A detailed historical flood record is available for the City of York consisting of annual maxima flood levels since AD 1877, with documentary accounts prior to this. A detailed analysis of long-term flood seasonality requires confidence in the accuracy and completeness of flood records; as a result the augmented flood series are analysed using three strategies: firstly, considering all recorded floods since AD 1600; secondly, through detailed analysis of the more complete record since AD 1800; and finally, applying a threshold to focus on high-magnitude flood events since AD 1800. The results identify later winter flooding, particularly in the second half of the twentieth century, with a notable reduction in summer flood events at York during the twentieth century compared to previous centuries. Flood generating mechanisms vary little between the periods considered, with a general pattern of stability in the ratio of floods incorporating a snowmelt component.

1 Introduction

The application of historical information (documentary and sedimentary) in assessing flood risk has expanded considerably in recent years (Brázdil et al. 1999, 2006; Glaser and Stangl 2003; Böhm and Wetzel 2006; McEwen and Werritty 2007; Glaser

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et al. 2010). Studies incorporating historical flood information have primarily focused on their value in reassessing high-magnitude flood frequency (Benito et al. 2004; Barriendos and Rodrigo 2006), the spatial distribution of flooding (Macdonald 2006), or the societal implications of extreme events (Brázdil et al. 2010), with few previous studies considering flood seasonality (McEwen 2006). The lack of previous analysis examining historical flood seasonality is a function of the limitations often imposed by data availability, quality and temporal distribution.

Previous studies examining flood seasonality have primarily focussed on gauged river flow records (Black and Werritty 1997; Cunderlik et al. 2004), with the average gauged record in the UK consisting of approximately 35-years of data with only a handful of sites exceeding 75-years in length (Marsh and Lees 2003). Climatic variability witnessed within recent decades has raised concerns that future extreme events cannot be accurately forecast from relatively short hydrological records (Mudelsee et al. 2003, 2004). Therefore, an alternative approach is required which uses more than just gauged river flow series, historical records present an important opportunity for extending and improving understanding of future climatic and hydrological variability through an improved appreciation of long-term variability.

The historical flood record for the City of York is one of the most detailed in the UK (Macdonald and Black 2010). The record consists of an Annual Maximum (AM) series of river flow levels in central York since 1877, preceded by an intermittent documentary record back to AD 1263 (Symons 1893; Macdonald 2004), a gauged flow record is available for Skelton 6 km upstream of York since 1957. The length of the AM series combined with detailed documentary accounts from the city provides a rare opportunity to assess long-term variability in flood seasonality.

This paper examines flood seasonality at York throughout the period AD 1600–2000. Although intermittent records are available prior to this, their paucity and lack of detail provides little additional information; as a result the period AD 1200–1599 is not considered within this paper. More specifically, the objectives of this paper are as follows:

(a) To identify fluctuations and trends in flood seasonality for the River Ouse at York since 1600;
(b) to present a robust approach for assessing long-term variability in flood seasonality; and
(c) to describe and compare the generating mechanisms that have resulted in flooding at York during the period since 1600.

2 The Ouse basin

The Yorkshire Ouse catchment is located in northeast England (Fig. 1) and has an area of 3315 km^2 upstream of Skelton (on the northern margin of York). Upstream of the city of York the main tributaries of the River Ouse are the Rivers Swale, Ure and Nidd, together draining much of the Northern Pennines. Precipitation totals vary throughout the catchment, ranging from in excess of 1800 mm a^{-1} in upland areas to less than 600 mm a^{-1} in the Vale of York and adjacent lowland regions (Meteorological Office 2002). Land use varies throughout the catchment, with predominantly arable and occasional pastoral farming in lowland areas (Dennis et al. 2003), at higher altitudes land use alters from grassland to rough grazing,

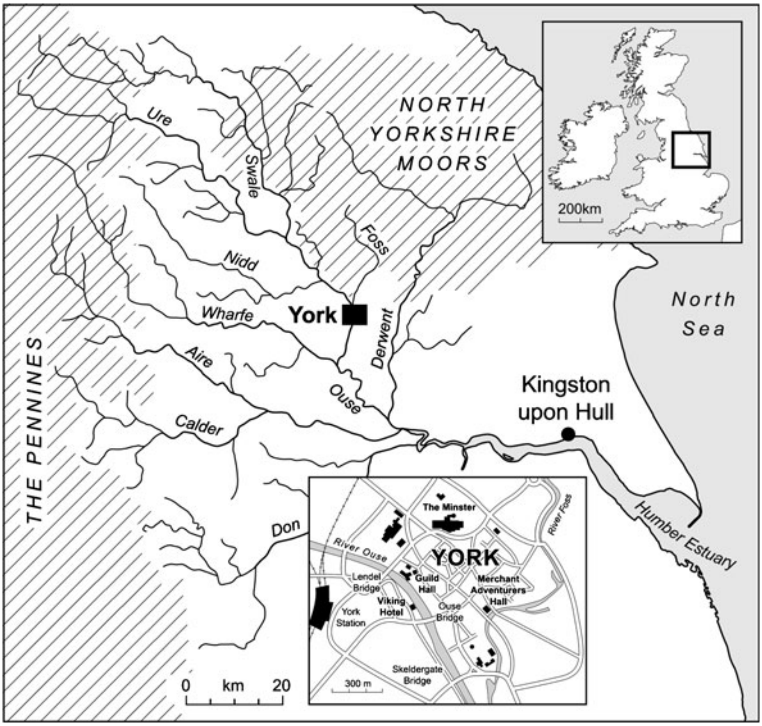

Fig. 1 The River Ouse and its tributaries

heathland and moorland. The influence of drainage and particularly gripping in the Upper Pennines is discussed in detail by Longfield and Macklin (1999); they determined that land use alterations are unlikely to significantly influence flooding in the lower catchment of the River Ouse as relatively small changes within the headwaters are aggregated out by the time waters reach the lower catchment, a view supported by Archer (2007) when looking at the Severn catchment (Wales–England border). Whilst much research has focussed on the impact of land use on relatively small flood events (e.g. Climent-Soler et al. 2009), little research either modelled or field instrumented has attempted to undertake this analysis with rarer high-magnitude events. Wheater and Evans (2009) postulate that the impact of urbanisation is potentially reduced during large flood events, whilst O'Connell et al. (2005) identify that there is very limited evidence that local changes in runoff propagate downstream. The changing nature of climate and catchment land use throughout the historical period may have caused many changes within the river regime, potentially manifesting as 'flood rich' and/or 'flood poor' periods (Starkel 2002; Benito and Thorndycraft 2005). However at York, Macdonald and Black (2010) identified a phase of increased flooding around AD 1625, but no significant change in flood frequency over the period AD 1800–2000. A view supported at a European scale by Mudelsee et al. (2003), but contrasting to the findings of Macklin and Rumsby (2007) when examining British upland catchments, as they identified a decrease in flood frequency based on geomorphologically-inferred flood events over the last 50 years. The principal flood generating mechanisms within the catchment during the instrumental period (*c*.1950–) are persistent rainfall over a saturated catchment associated with westerly and cyclonic systems and combined rainfall–snowmelt events (Macdonald 2004).

3 Data and methods

3.1 Data sources

Two discrete forms of data are available at York, the instrumental river level record since AD 1877 and historical documentary sources (Fig. 2; Macdonald 2004). The instrumental series is unique in that it provides the longest continuous AM flow series in the UK. Other long river flow series are Feildes Weir (River Lee–River Thames tributary) from 1879 and Teddington (River Thames), from 1883. The instrumental series at York is derived from AM river levels obtained from adjacent stageboards (all within ∼200 m) at Ouse Bridge (1877–1892), Guildhall (1893–1963) and the Viking Hotel (from 1963), producing an augmented stage series. These stage records were used with flow data from Skelton to produce a rating curve, allowing a continuous series of AM flows to be produced for the period 1877–2000. Based on the analysis of historical documents (e.g. town descriptions and maps), it is possible to determine that the channel cross section has remained stable throughout the city reach during the last two hundred years, as the area is confined within a walled section with occasional landings (bounded by Lendel and Ouse bridges; Fig. 1). The reach between Ouse Bridge and Skeltergate bridge has similarly remained relatively stable, based on Rocque's map of (1750). Examination of the records fails to identify any ice-jam floods within the documentary records (see Macdonald 2006 for discussion on the potential impacts of ice-jamming during

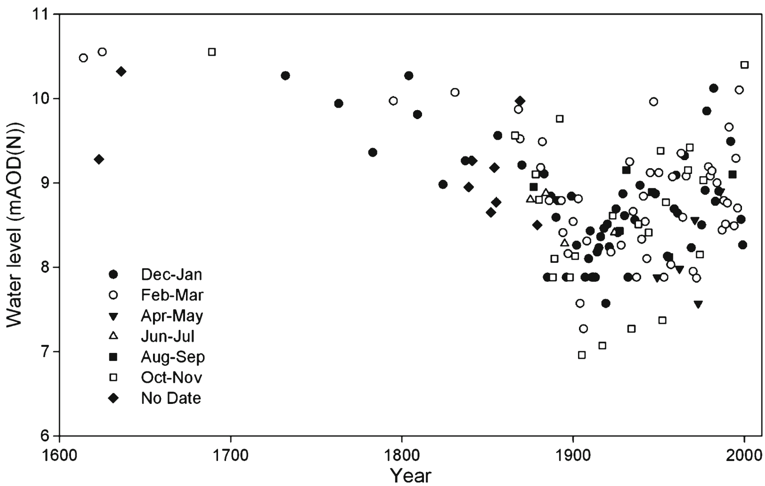

Fig. 2 Seasonality of flood events in central York

flood events on a British river). The City of York has three main bridges (Fig. 1), the most recently constructed, Skeldergate Bridge (1882) and Lendel Bridge (1863) are new bridges; the Ouse Bridge which was reconstructed in 1821, is the fifth bridge following Roman, Viking, medieval (destroyed during the flood of 1564) and sixteenth century bridges on the site. The influence of the historical bridges at high flow is difficult to estimate as little information remains (other than an engraving of the 1565–1810 bridge); the impact of the contemporary bridges appears minimal. During the floods of 2000 some localised backing-up of flow occurred through the Ouse Bridge, which had little impact on the overall water-levels upstream and downstream. Documentary accounts provide a detailed record of flooding at York from the early eighteenth century (e.g. Drake 1736); prior to this they are more sporadic in nature, often documenting only notable large floods (Macdonald and Black 2010). Documentary flood records frequently include basic information concerning date, height or magnitude of events, and often the causative mechanism i.e. rain, thaw or a combination of the two (McEwen 1987). The long record of flooding at York results from several influences, namely the presence of literate individuals linked to monastic, political and economic activities within the city; a detailed discussion of sources at York is provided in Macdonald (2004) and Macdonald and Black (2010).

The British Hydrological Society's *Chronology of British Hydrological Events* (CBHE) database is an online depository of records documenting significant hydrological events and is a valuable centralised resource for identifying non-instrumental hydrological information within the United Kingdom (Black and Law 2004). The information extracted from the CBHE website was compiled with data collated from the City of York archives and documentary sources. These were extensively assessed and cross-referenced (with coeval independent sources where available) to validate flooding accounts, ensuring that potentially spurious records were removed (Macdonald and Black 2010). The earliest records (prior to AD 1600) only record spectacular or catastrophic flooding (e.g. "At Christmas time Anno Domini, 1263, the inundation of the river was so great that it flowed over the end of the bridge towards Micklegate" (Widderington 1662, p.116)), providing a partial representation of flooding during this period, as smaller events remained unrecorded. McEwen (2006) identified similar incompleteness in flood records in the River Tay catchment prior to AD 1800. The heterogeneous nature of descriptive accounts and increased flood recording nearing the present result from improved literacy and increased personal and governmental interest in the state of the river, and/or river level variability and is evidenced at numerous sites across Europe during this period (Camuffo et al. 2000). Therefore, in consideration of the increased frequency of accounts recording flooding from AD 1600, the analysis will examine the data from this period onwards.

3.2 Timescales

This paper considers the seasonality of flooding at York through three different timescales: (a) flood seasonality over the complete period, AD 1600–1999; (b) all data since AD 1800, permitting greater confidence to be placed within more recent records, where record density is greatest; and, (c) considers the data since AD 1800 adopting a high threshold, the application of a high threshold compensates for the potential exclusion of smaller flood events.

The analysis of the period since AD 1600 includes the Little Ice Age (LIA; Bradley and Jones 1992), a period of perceived non-stationarity as climatic conditions were cooler and winters more severe (potentially more snow accumulation), with subsequent warming nearing the present. The period since AD 1800 is one of general warming following the LIA and a period of improved recording (of a potential 200 years, 166 AM floods are recorded). The use of the threshold permits analysis of only the largest flood events, the threshold level applied represents the median discharge, derived from the documentary and instrumental AM series, for the period AD 1800–2000, which is 350 m^3 s^{-1} (a level of 8.75 m above Ordinance Datum (Newlyn; AOD(N)). The median discharge is calculated using the instrumental series since 1877 and record levels (estimated discharges) from AD 1800–1877 (Macdonald 2004). Threshold exceedance analysis is a recognised tool in flood frequency analysis when applying historically augmented datasets (Stedinger and Cohn 1986; Parent and Bernier 2003; Macdonald et al. 2006). Removal of the smallest events provides a more realistic comparison between centuries (after data normalization), as recent events (within the instrumental series) below the threshold are removed, events of a magnitude that are unlikely to have been recorded within historical documentary accounts.

3.3 Seasonal frequencies

Approaches applied in previous studies have transferred flood seasonality data into a directional statistic (Black and Werritty 1997), or calculated a relative flood occurrence frequency for each month (Cunderlik et al. 2004). These approaches are unsuitable within this study as the non-continuous nature of documentary flood recording often results in non-specific flood dates (month only). This paper applies a normalization approach to the number of recorded events within each 50-year period. The normalization is based on the creation of an equal weighting of events in any given period, so that comparison may be undertaken across the different periods (Kundzewicz and Robson 2004). The normalization approach is based on representing equally the number of recorded events occurring within each monthly (or bi-monthly) period, the number of floods within each given month is divided by the total number of events occurring in the given period. Therefore, seasonality character and changes in seasonality are reliable and independent from the data completeness (Camuffo et al. 2000). Monthly and bi-monthly frequencies are considered, monthly frequencies are used to examine minor changes in flood event timing, whilst bi-monthly are used as Black (1992) determined that in Northern Britain this approach provided more specific information than the directional statistics method. The bi-monthly approach has additional benefits when being applied to documentary data as it enhances confidence in the correct recording of flood seasonality.

3.4 Flood generating mechanisms

Flood generating mechanisms are characterised into two categories: rain; and rain on snow (thaw). It is difficult to identify from some accounts the role and extent that rain may have contributed to thaw events and this may have varied across the catchment; therefore, within this study snowmelt and snowmelt with rainfall are considered as a single category. Analysis of the flood generating mechanisms is dependent on assessing the hydrometeorological information (temperature and synoptic conditions) of the catchment (Table 1; Rumsby and Macklin 1994). Where documentary records indicate the cause of flooding, these are verified using the Central England Temperature Series (CETS; from 1772) and synoptic conditions derived from Jenkinson and Collinson (1977) British Isles circulation variables dataset. The Jenkinson and Collinson circulation variables classify daily circulation types over the British Isles since AD 1880, applying the subjective approach devised by Lamb (1972). Flood accounts in which an explanation of the flood generating mechanism are analysed against the CETS (to determine changes within temperature) and the Jenkinson and Collinson circulation variables to determine the principal circulation type on the day of flood and preceding days. The British Rainfall (1860–1991) series was scrutinised to establish whether any records document extreme precipitation or heavy snowfall within the region for the period preceding the flood event.

Table 1 Reconstructed synoptic and temperature variations prior to flood events (for floods of specific known date prior to 1900)

Year	Synoptic conditions[a]	CETS (°C; **day of flood** and previous 9 days)	Probable cause
12/01/1790		**9.4**, 6.6, 2.2, 1.6, 1.0, 4.2, 4.1, 5.9, 5.6, 7.4	Rain
09/02/1795		**6.5**, 3.4, −0.6, −2.0, −0.6, −1.6, −2.0, −0.4, 0, −2.7.	Rain/Thaw
01/01/1809		**2.6**, 2.4, 4.4, 3.9, 0.2, 0.9, −3.1, −1.6, −1.3, −1.8	Thaw
10/01/1824		**6.7**, 5.7, 2.6, 2.5, 3.1, 3.7, 1.9, 3.8, 7.9, 8.1	Rain
10/02/1831		**9.1**, 11.4, 10.5, 8.69, 0.6, 1.0, 2.1, 1.1, −0.5, 1.2,	Rain/Thaw
20/12/1837		**9.1**, 8.9, 9.5, 8.5, 5.1, 3.0, 2.8, 2.8, 1.7, 2.3	Rain
23/07/1840		**12.7**, 13.7, 15.9, 13.3, 11.4, 13.1, 14.1, 16.8, 16.5, 14.9	Rain
15/11/1866		**9.0**, 5.2, 8.6, 11.3, 8.9, 6.7, 3.9, 7.9, 10.9, 10.5	Rain
05/02/1869		**9.5**, 10.7, 10.3, 6.2, 8.2, 9.4, 9.1, 7.4, 9.0, 6.2	Rain
19/07/1875		**15.6**, 16.2, 17.8, 18.5, 18.7, 18.5, 18.2, 17.2, 17.7, 17.8	Rain
10/03/1881	W, W, W	**11.5**, 8.1, 7.5, 9.7, 8.9, 5.4, 3.5, 1.8, −0.5, −0.5	Rain/Thaw
29/01/1885	C, C, S	**9.7**, 7.9, 6.8, 3.9, 2.3, 1.0, −0.1, −0.7, −0.6, 0.8	Rain/Thaw
22/03/1886	SW, SW, ASW	**11.4**, 8.9, 11.6, 10.0, 7.1, 3.1, 1.4, −0.3, 0.9, 0.1	Rain/Thaw
20/01/1887	W, W, CNW	**4.6**, 6.5, 2.5, −1.2, −0.9, 0.4, 0.4, −0.9, 3.1, 1.5	Rain/Thaw
25/11/1888	W, W, W	**11.4**, 11.3, 10.8, 8.9, 6.0, 6.9, 10.0, 9.2, 10.6, 12.3	Rain
24/10/1889	CE, CE, AC	**7.5**, 8.2, 9.1, 8.9, 8.1, 9.8, 9.3, 9.8, 10.7, 7.8	Rain
27/01/1890	W, W, NW	**5.3**, 7.1, 7.6, 5.5, 4.0, 4.1, 2.8, 3.9, 6.9, 7.3	Rain
11/12/1891	CW, W, W	**5.4**, 8.7, 7.9, 5.0, 7.0, 7.5, 9.5, 9.8, 8.7, 7.3	Rain
16/10/1892	CE, E, N	**7.0**, 7.8, 8.9, 8.3, 6.1, 6.9, 9.6, 8.7, 8.0, 9.7	Rain
03/03/1893	C, W, ACS	**7.0**, 8.9, 6.1, 2.9, 2.3, 2.1, 1.4, 0.1, 0.9, 2.8	Rain/Thaw
12/02/1894	W, CW, NW	**5.5**, 8.3, 7.4, 7.5, 7.6, 10.3, 6.5, 6.2, 6.9, 8.3	Rain
27/07/1895	C, C, C	**16.8**, 18.4, 17.4, 15.5, 14.1, 13.9, 14.4, 14.3, 15.7, 17.6	Rain
06/12/1896	C, C, C	**5.4**, 6.3, 6.5, 6.6, 3.7, 0.2, −0.9, 2.3, 3.2, 4.6	Rain
10/02/1897	SW, W, AC	**6.2**, 6.9, 4.3, 3.6, 2.6, 4.2, 3.5, 2.4, 1.5, 1.3	Rain
19/10/1898	CE, C, C	**10.9**, 11.6, 12.0, 9.6, 9.2, 9.3, 7.9, 8.2, 9.6, 10.3	Rain
22/01/1899	SW, C, C	**8.9**, 9.6, 8.5, 9.3, 5.9, 3.7, 6.8, 7.0, 4.9, 6.2	Rain

C Cyclonic; *A* Anticyclonic *S* Southerly; *W* westerly; *N* Northerly; *E* Easterly; or combination e.g. *CE* cyclonic easterly

[a]Synoptic conditions on the day of the flood and two previous days (3 day history). Weather types based on Jenkinson and Collinson (1977) classification

Documentary records were considered as they often include details documenting the cause of flooding, e.g.

> On the 9th of February [1795], the River Aire, which had been frozen for a considerable time, exhibited a most appalling scene, occasioned by a rapid thaw and heavy rain, which broke up the ice... All the principle [principal] river in the county of York exhibited a similar spectacle, and the roads in various places were laid so deep in water as to stop the mails and coaches several days (Schroeder 1851, p 181).

This account is supported by the daily CETS, which clearly identifies that rapid warming took place two days prior to the flood on the 9th of February, with an extended period of mean daily temperatures ≤0°C preceding the 9th (6.5 [Feb. 8th], 3.4, −0.6, −2.0, −0.6, −1.6, −2.0, −0.4, 0, −2.7, −3.8 [Jan. 29th] (°C)). The analysis of prior temperature records provides valuable information on the generating mechanisms. Although the CETS provides an opportunity to assess long-term temperature variability it does have limitations when applied to the River Ouse catchment. In part this is a result of the elevated relief in large parts of the catchment, which may be several degrees cooler than that recorded by the CETS. The CETS represents an area covering lowland central England, large parts of the Ouse catchment are outside the CETS area, which has important implications when considering the characteristic process for flood generating mechanisms.

4 Seasonality analysis

4.1 Variability with 50-year periods

Inevitably when considering flood seasonality natural stochastic variability exists within months and seasons, but aspects of the frequency of flood events within the bi-monthly periods deserves further discussion, during the 50-year periods considered (Table 2). The second half of the eighteenth century provides a more complete depiction of flood seasonality compared to early periods, with the notable bi-monthly period being August–September AD 1700–1750, were a high number of events are recorded (4), greater than any other period (Table 2). The periods AD 1800–1849 and 1850–1899 present little of particular note except for a relatively high summer flood frequency compared to the twentieth century (Table 2; Fig. 3). The period AD 1900–1949 and AD 1950–1999 both experience an increased frequency of flooding within the bi-monthly period February–March and a reduction in summer flood events (Table 2). Comparison of the frequency of events when considered over a sliding 50 year window identifies the relatively low number of events in the earlier record compared to the later record, even when normalised and missing events are considered. Figure 3 illustrates that almost all missing events would need to be included as DJF flood events (an unlikely scenario) for the early period to exhibit a similar frequency of early–mid twentieth century DJF flood events; the normalised curve presented indicates a reduced frequency compared to the present day (Fig. 3).

Table 2 Seasonality (bi-monthly) of recorded floods for varying 50-year periods (percentage of floods within any bi-monthly period for the given 50-year period)

		Years							
		1600–1649	1650–1699	1700–1749	1750–1799	1800–1849	1850–1899	1900–1949	1950–1999
Bi-monthly	Dec–Jan	0 (0)	4 (66.7)	1 (16.7)	4 (23.5)	11 (44)	15 (36.6)	22 (44)	16 (32)
	Feb–Mar	2 (66.7)	0 (0)	3 (50.0)	4 (23.5)	5 (20)	9 (22)	16 (32)	21 (42)
	Apr–May	0 (0)	0 (0)	1 (16.7)	2 (11.8)	2 (8)	1 (2.4)	1 (2)	4 (8)
	Jun–Jul	0 (0)	1 (16.7)	1 (16.7)	0 (0)	3 (12)	6 (14.6)	1 (2)	0 (0)
	Aug–Sep	1 (33.3)	0 (0)	0 (0)	4 (23.5)	3 (12)	2 (4.9)	3 (6)	2 (4)
	Oct–Nov	0 (0)	1 (16.7)	0 (0)	3 (17.6)	1 (4)	8 (19.5)	7 (14)	7 (14)
Total		3	6	6	17	25	41	50	50

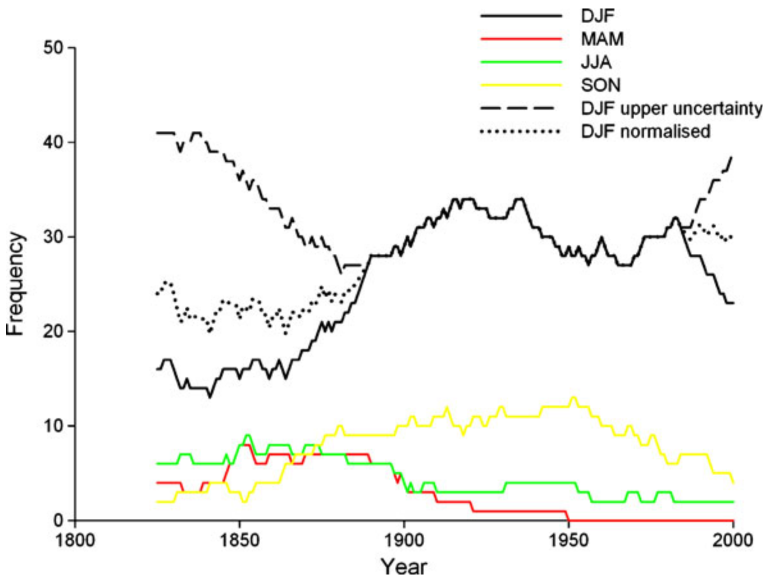

Fig. 3 50-year cumulative frequency of floods by season since 1800 plotted by central point, including normalised (compensating for missing data during the period 1800–1863) and upper potential frequency curves for DJF based on missing data

4.2 Century timescale variability in flood seasonality

4.2.1 AD 1600–1799

The limited number of detailed flood accounts prior to AD 1800 results in greater weighting being given to occasional high magnitude floods in comparison to later periods (Table 2), this potentially distorts flood seasonality in the absence/presence of a few large floods in a given bi-month period. The flood events that include dates indicate that flooding predominantly occurs in the December–January (4 recorded events) and February–March (2 recorded events) bi-monthly periods, a pattern comparable to later periods. Variability within the period AD 1600–1799 (Fig. 4) appears to be present within the records; as a low number of floods recorded within the December–January bi-monthly period and comparably greater presence of flood events within the February–March and April–May periods in the eighteenth century is notable, though this is based on a small number of records, making it challenging to place reasonable confidence in any apparent shift.

4.2.2 AD 1800–1999

Comparative analysis of the period AD 1800–1999 using the AM series and documentary data required the normalization of the AD 1800–1899 data, as a result of an imbalance in the number of recorded floods during the two centuries. There are distinct changes in the timing of flooding between the nineteenth and twentieth centuries, with a considerable increase (15.8%) in February–March floods and a decrease (12.6%) in recorded floods in the June–July period (Table 3; Fig. 5), the

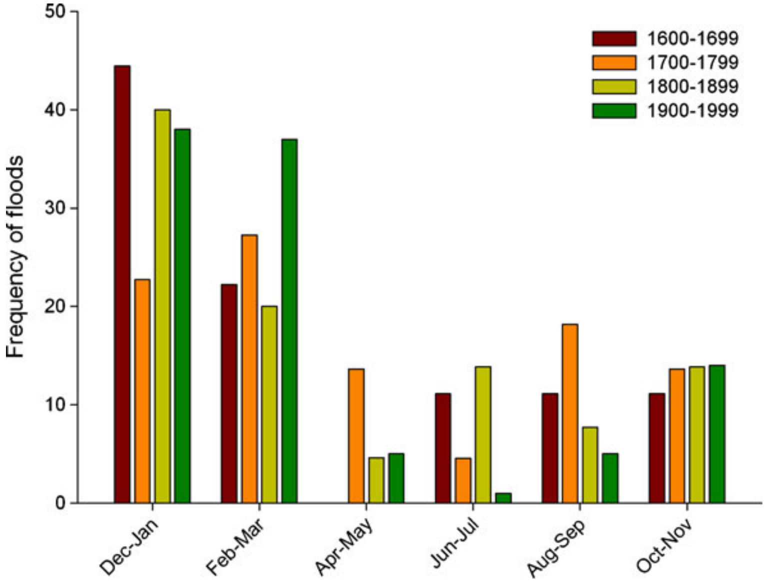

Fig. 4 Seasonality of recorded (AM) floods at York since 1600 (normalised)

variability within other bi-monthly periods is relatively small (≤±3%). The variable quality of flood event recording in the period AD 1800–1876 can in part be overcome by applying a threshold, as it is reasonable to expect that the largest events would be recorded as notable floods.

4.2.3 Comparison between AD 1600–1799 and 1800–1999

Comparison of the two periods AD 1600–1799 and AD 1800–1999 (while recognising the limited data availability for the period 1600–1799) identifies an increase in February–March flooding (Fig. 4). The decreasing frequency of flooding in the December–January period is evident when the early period (1600–1750) is included (Table 2), otherwise it appears relatively stable (slightly decreasing) since AD 1800. Flood seasonality appears relatively stable over other bi-monthly periods during the four hundred year period.

Table 3 Bi-monthly change in flooding on the River Ouse, 1800–1999

	Percentage change between 19th and 20th century (all floods)	Percentage change in high magnitude events (>8.75 mAOD(N))
Dec–Jan	−1.4	−21.1
Feb–Mar	+15.8	+24
Apr–May	−0.5	+2.6
Jun–Jul	−12.6	−3.3
Aug–Sep	−2.6	+1.2
Oct–Nov	+0.4	−3.5

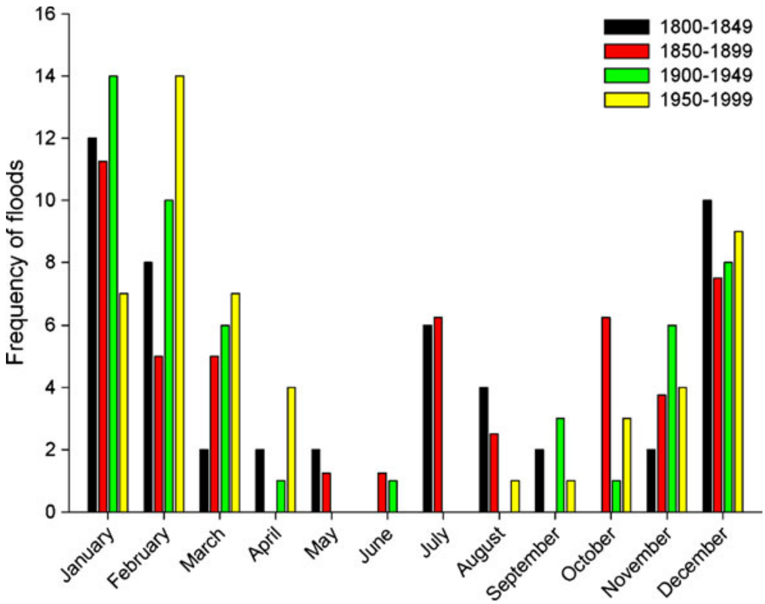

Fig. 5 Seasonality of the annual maxima flood during 50-year (normalised) periods since 1800 at York

4.3 Analysis of flood seasonality applying a high threshold

Analysis of flood seasonality (from AD 1800) above the threshold (see Section 3.2 for explanation of threshold selection) highlights the shift from the December–January to the February–March period over four consecutive 50-year periods (Table 2). The increased frequency of high magnitude flood events in the February–March period (13 floods) within the period AD 1950–1999 compared to previous periods (2; 5; 5 flood events in previous 50-year periods) highlights the shift in flood seasonality (Fig. 6). Consideration of total events within the period also highlights a considerable increase in high magnitude events, with 29 during the period 1950–1999, compared to 5, 15, 10 flood events in the previous 50-year periods (Table 4). This movement in seasonality is even more pronounced when considered at a century scale, with an increase of 24% in flood seasonality in the February–March period in the period AD 1900–1999, compared to AD 1800–1899 (Table 3).

4.4 Flood generating mechanisms

4.4.1 Thaw

Few flood events on the River Ouse are recorded which are simply generated from the thawing of snow and which have an estimated level, the earliest event is that of AD 1614 which is described as:

> at York it began to snow and freeze on January 16th, and the frost continued unbroken, with occasional snow, until March 7th, by which time the depth of snow was greater than in any other year within living memory. When the thaw came there was a great flood, but without rain... (Brooks and Glasspoole 1928)

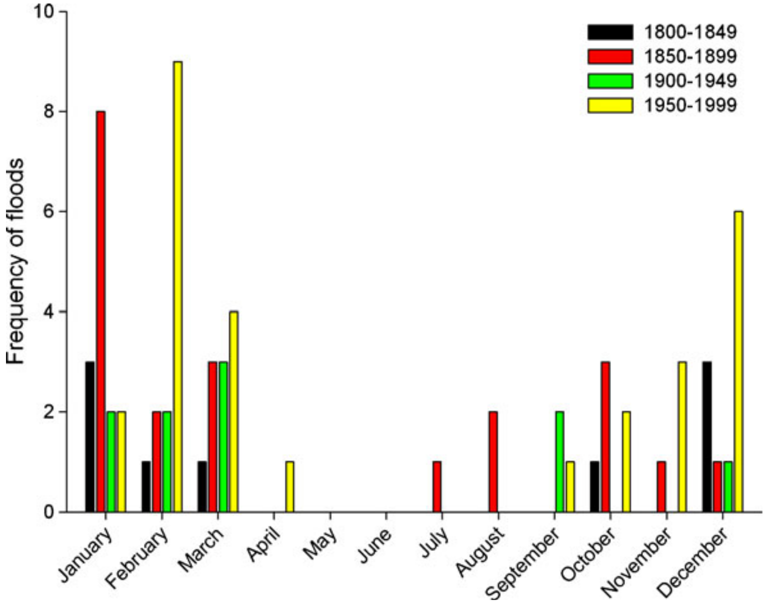

Fig. 6 Seasonality of floods above a threshold (8.75 mAOD(N)) for the four 50-year periods since AD 1800

No additional information concerning the February 1625 flood is available at York, but an "exceptional great storm flood" is recorded within the North Sea at the end of February (old calendar) AD 1625, with accounts of a westerly to northwesterly storm by Lamb and Frydendahl (1991). A significant component of this event's historical notoriety results from the severe tidal flooding across much of Holland

Table 4 Frequency and seasonality of snowmelt and rainfall generated flood events for the largest floods (8.75 mAOD(N)/350 $m^3\ s^{-1}$)

	1800–1849		1850–1899		1900–194		1950–1999	
	Thaw and rain	Rain	Thaw and rain	Rain	Thaw and rain	Rain	Thaw and rain	Rain
January	1	1	2	1	1	1	2	0
February	1	0	0	1	2	0	2	7
March	0	0	4	0	2	1	2	2
April	0	0	0	0	0	0	0	1
May	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0
July	0	1	0	2	0	0	0	0
August	0	0	0	1	0	0	0	0
September	0	0	0	0	0	2	0	1
October	0	0	0	2	0	0	0	2
November	0	0	0	1	0	0	0	4
December	0	1	0	1	0	1	1	5
Total	2	3	6	9	5	5	7	22

No normalization undertaken

and coastal Germany, the accounts also detail the role of ice in causing ice blockages within rivers and flooding in France; which was identified by Lamb and Frydendahl (1991) as unusual for a solely tidally driven event. Given the descriptions available and the synoptic details presented it is likely that flooding at York often resulted from heavy rainfall and thaw.

Within the nineteenth century only one flood event (1809) was recorded as solely generated by thaw, with rainfall contributing to all other events recorded as having a thaw component. The February 1831 flood is ascribed to thaw and rainfall within the Ouse catchment (Yorkshire Water Authority 1980), with other sites across Britain also suffering extensive flooding during this period (The Examiner 1831).

The proportion of flood events that incorporate a thaw component within flood generation has remained stable since AD 1800 (Table 5). The ratio of recorded snowmelt generated flood events against rainfall only generated floods is 1:2.98 (48/143; Table 5) over the period AD 1800–1999. There is little evidence to suggest that the largest flood events (>350 $m^3\ s^{-1}$) are more frequently generated by snowmelt floods within the Yorkshire Ouse catchment, as 20/59 floods exceeding the threshold are identified as including a snowmelt component (Table 4), a ratio of 1:2.95. Examination of the frequency of thaw events during the period since 1900 suggests that the decadal frequency of events has remained relatively stable with an average of 3.2 events per decade, the 1980s only witnessed one snowmelt event, though there is some variability between decades. The comparable number of thaw events during the nineteenth and twentieth century is a little surprising as the late nineteenth century is recognised across much of Europe to be an unusually cold period (Böhm et al. 2010); a potential explanation may be that although the number of snowmelt events has remained the same throughout the timeframes considered, the potential quantity of snow accumulation within the upland parts of the catchment may have varied. With more frequent partial melting and reduced accumulation (potentially reduced snowfall) reducing the overall impact of snowmelt, unfortunately rates and depths of snow accumulation are not routinely recorded for this region.

Table 5 Frequency and seasonality of snowmelt and rainfall generated flood events based on the synoptic and temperature records augmented with documented accounts detailing generating mechanisms (brackets represent normalised values)

	1800–1849		1850–1899		1900–194		1950–1999	
	Thaw and rain	Rain	Thaw and rain	Rain	Thaw and rain	Rain	Thaw and rain	Rain
January	1 (3)	1 (3)	4 (7)	2 (4)	8	6	3	5
February	2 (7)	0	1 (2)	1 (2)	4	6	7	7
March	1 (3)	0	4 (7)	0	2	4	3	4
April	0	1 (3)	0	0	0	1	0	4
May	0	0	0	1 (2)	0	0	0	0
June	0	0	0	1 (2)	0	1	0	0
July	0	3 (10)	0	4 (7)	0	0	0	0
August	0	1 (3)	0	2 (4)	0	0	0	1
September	0	1 (3)	0	0	0	3	0	1
October	0	0	0	4 (7)	0	1	0	3
November	0	0	0	2 (4)	0	6	0	4
December	2 (7)	2 (7)	1 (2)	1 (2)	3	5	2	6
Total	6 (20)	9 (29)	10 (18)	18 (34)	17	33	15	35

4.4.2 Intense precipitation events

Intense precipitation events are recognised as an important flood generating mechanism (McEwen 2006), but there influence in flooding at York is difficult to ascertain as often limited information is recorded. Where accounts do exist they are often focused at the local level, which often fail to propagate downstream to York when recorded in sub-catchments, or correspond to large flood events within York itself. Notably intense precipitation events often occur within the summer months and are described as significant and highly destructive within sub-catchments, particularly within upland regions (Pennines—Fig. 1); an account of the flood at Gunnerside on the upper River Swale represents a good example:

> [On the 25th July, 1888] At Gunnerside the large bridge which crossed the river at this place was entirely swept away; also the road leading from the village to the bridge, for about 500 yards, rendering it impassable, by the beck which flows through the village. Its proper course is filled up, and it rushes over the top of the road... (The Leeds Mercury 1888).

With a report in the *Darlington and Stockton Times* recording the mechanisms responsible for generating the flood:

> Rain had fallen for days past west of Richmond [N. Yorkshire] and at about 5.0 p.m [17.00 h]. on Wednesday a sudden and unexpected flood rushed down Arkengarthdale and the upper reaches of Swaledale. Most of the walls on the flatts [sic] were washed away, and many hundreds of acres were under water... At 4.0 p.m [16.00 h]. a terrific downpour, which must have commenced in the higher reaches of the dale, began to move eastwards; the river now being bank high... The bridge over the Swale at Gunnerside had one arch washed away at 6.0 p.m [18.00 h], after which the water seemed to abate a little; but at 8.0 p.m [20.00 h]. another 'freshet' came down which swept away the remainder of the bridge (Williams 1957).

A number of events of this nature are recorded within the Ouse catchment since the sixteenth century, but fail to generate flows of sufficient volume to cause flooding at York.

4.4.3 Long duration precipitation causing flood events

The principal flood generating mechanism at York is extensive and prolonged precipitation over much of the catchment; with a high number of flood records detailing extended periods of rainfall prior to flooding and/or comment on saturated catchments e.g.:

> The late rainy season has so saturated the land that the whole of the last extraordinary rainfall ran rapidly off into the streams, and in that short period the North Riding rivers have risen from summer level to a state of flood. (Symons 1866).

The first account of long duration precipitation within the Ouse catchment not incorporating a thaw component is the AD 1689 flood. The accounts detailing this flood fail to include any additional information concerning the generating mechanisms, but an account of flooding on the River Tyne describes the events as:

> the great and continual rains, for these ten days past, occasioned here on Saturday last so great a flood, that, meeting with the Spring-Tyde [sic], it overflowed all the cellers [sic] and shops near the key [sic]... (*London Gazette*, Thursday, October 24, 1689)

Floods are also documented on the rivers Wear and Trent to the north and south respectively of the Ouse catchment. The combination of events within October 1689 suggests that the flooding in the River Ouse was probably the result of the same slow moving frontal system that generated flooding across much of northeast England.

The majority of flood events within the nineteenth and twentieth centuries are generated as a result of long duration precipitation events, including the flood of November 2000, the largest since AD 1689 (Fig. 1).

4.4.4 Synoptic analysis

Analysis of the synoptic conditions associated with flooding since AD 1880, the start of the Jenkinson's objective weather classification, identify that no noticeable

Table 6 Frequency (as percentage) of synoptic conditions associated with maximum peak floods of known date since 1880 (using the synoptic conditions in the 10 days prior to each flood event)

	1880–1899	1900–1919	1920–1939	1940–1959	1960–1979	1980–1999	Average
A	**10**	8	7	**12**	2	6	7
ANE	0	0	0	1	0	1	0
AE	1	0	1	0	0	1	0
ASE	1	0	0	1	2	1	1
AS	3	1	1	2	1	1	1
ASW	2	2	1	1	0	3	1
AW	3	3	4	3	1	2	3
ANW	1	1	0	1	0	1	1
AN	1	1	1	2	1	0	1
NE	2	1	0	1	2	3	1
E	3	0	2	1	1	1	1
SE	4	1	1	3	2	3	2
S	8	2	4	7	**10**	5	6
SW	9	**17**	**11**	**10**	**12**	**15**	**12**
W	**15**	**14**	**15**	**9**	**11**	**13**	**13**
NW	5	3	8	3	6	3	5
N	1	5	4	2	0	3	2
C	**19**	**27**	**18**	**23**	**29**	**27**	**24**
CNE	1	2	2	1	0	0	1
CE	1	0	1	0	4	1	1
CSE	2	1	3	3	2	1	2
CS	1	4	5	3	5	2	3
CSW	5	5	6	5	4	7	5
CW	3	5	7	5	4	2	4
CNW	2	1	4	3	2	2	2
CN	0	2	2	2	0	1	1

Notable (>10%) scores emboldened
Weather types based on Jenkinson and Collinson (1977) classification

Table 7 Bi-monthly breakdown of synoptic conditions associated with flooding with 3 day (10 day) synoptic histories

	December–January		February–March		April–May		June–July		August–September		October–November	
	Frequency	%	Frequency	%	Frequency	%	Frequency	%	Frequency	%	Frequency	%
A	5 (29)	4 (7)	5 (37)	4 (9)	0 (3)	0 (6)	**1 (2)**	**17 (10)**	**3 (10)**	**20 (20)**	2 (11)	6 (6)
ANE	0 (0)	0 (0)	0 (2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
AE	0 (1)	0 (0)	0 (2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (1)	0 (2)	0 (0)	0 (0)
ASE	0 (0)	0 (0)	1 (8)	1 (2)	0 (1)	0 (2)	0 (0)	0 (0)	0 (0)	0 (2)	0 (1)	0 (1)
AS	1 (6)	1 (1)	0 (6)	0 (1)	0 (1)	0 (2)	0 (0)	0 (0)	1 (1)	7 (2)	0 (1)	0 (1)
ASW	0 (2)	0 (0)	4 (10)	3 (2)	0 (0)	0 (0)	**1 (1)**	**17 (5)**	0 (0)	0 (0)	0 (2)	0 (1)
AW	4 (13)	3 (3)	3 (11)	2 (3)	0 (1)	0 (2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (5)	0 (3)
ANW	1 (3)	1 (1)	2 (3)	2 (1)	0 (0)	0 (0)	0 (1)	0 (5)	0 (0)	0 (0)	0 (1)	0 (1)
AN	2 (2)	2 (0)	0 (1)	0 (0)	1 (1)	7 (2)	**1 (1)**	**17 (5)**	0 (1)	0 (2)	0 (2)	0 (1)
NE	0 (1)	0 (0)	2 (4)	2 (1)	0 (2)	0 (4)	0 (0)	0 (0)	**2 (2)**	**13 (4)**	3 (6)	8 (3)
E	1 (5)	1 (1)	1 (3)	1 (1)	0 (0)	0 (0)	0 (2)	0 (10)	0 (1)	0 (2)	1 (4)	3 (2)
SE	1 (4)	1 (1)	1 (13)	1 (3)	0 (3)	0 (6)	0 (0)	0 (0)	0 (2)	0 (4)	0 (5)	0 (3)
S	3 (25)	2 (6)	6 (26)	5 (6)	0 (2)	0 (4)	0 (0)	0 (0)	1 (1)	7 (2)	0 (7)	0 (4)
SW	**21 (69)**	**16 (16)**	**19 (48)**	**15 (11)**	**3 (7)**	**20 (14)**	0 (1)	0 (5)	0 (2)	0 (4)	2 (14)	6 (8)
W	**17 (59)**	**13 (13)**	**21 (50)**	**17 (12)**	**1 (6)**	**7 (12)**	**1 (3)**	**17 (15)**	**1 (6)**	**7 (12)**	**3 (22)**	**8 (12)**
NW	10 (27)	8 (6)	6 (13)	5 (3)	1 (3)	7 (6)	0 (1)	0 (5)	1 (3)	7 (6)	2 (6)	6 (3)
N	4 (12)	3 (3)	2 (10)	2 (2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1 (6)	3 (3)
C	**34 (95)**	**26 (22)**	**23 (95)**	**18 (23)**	**6 (13)**	**40 (26)**	**1 (5)**	**17 (25)**	**3 (8)**	**20 (16)**	**11 (53)**	**31 (29)**
CNE	0 (0)	0 (0)	1 (4)	1 (1)	0 (0)	0 (0)	1 (1)	**17 (5)**	0 (0)	0 (0)	1 (4)	3 (2)
CE	1 (2)	1 (0)	0 (0)	0 (0)	1 (1)	7 (2)	0 (1)	0 (5)	1 (1)	7 (2)	1 (5)	3 (3)
CSE	2 (3)	2 (1)	2 (13)	2 (3)	0 (1)	0 (2)	0 (0)	0 (0)	0 (0)	0 (0)	1 (3)	3 (2)
CS	2 (14)	2 (3)	7 (16)	6 (4)	0 (1)	0 (2)	0 (0)	0 (0)	0 (2)	0 (4)	1 (5)	3 (3)
CSW	9 (30)	7 (7)	10 (22)	8 (5)	0 (0)	0 (0)	0 (0)	0 (0)	0 (3)	0 (6)	1 (4)	3 (2)
CW	12 (26)	9 (6)	7 (13)	6 (3)	1 (2)	7 (4)	0 (0)	0 (0)	0 (1)	0 (2)	3 (5)	8 (3)
CNW	2 (7)	2 (2)	2 (6)	2 (1)	0 (0)	0 (0)	0 (1)	0 (5)	0 (3)	0 (6)	1 (6)	3 (3)
CN	0 (5)	0 (1)	1 (4)	1 (2)	1 (2)	7 (7)	0 (0)	0 (0)	**2 (2)**	**13 (4)**	2 (2)	6 (1)

Notable (>10%) scores are presented in italics (1880–1999)

Weather types based on Jenkinson and Collinson (1977) classification long-term changes in the flood generating synoptic conditions are evident, based on 3 and 10 day timescales prior to flood events. In addressing concerns that the frequency of westerly events has reduced and cyclonic (C) events have increased during the twentieth century, analysis of 20-year periods which provide a more detailed depiction of variability in comparison to the 50-year signal considered appropriate for flood events evidence no clear indication of changing frequencies impacting on flood generating mechanisms, as considerable variability is present (Table 6). Anticyclonic (A) conditions are rarely associated with flooding in the UK, whilst the highest presence of systems associated with flooding are cyclonic (C 24%), westerly (W 13%) and south-westerly (SW 12%) systems (using the synoptic conditions in the 10 days prior to each flood event). Analysis of the synoptic conditions associated with different bi-monthly periods show little variability, the primary deviations are the increased presence of anticyclonic systems for flood events during summer (June–July and August–September bi-monthly periods), with a corresponding decrease in south-westerlies (Table 7). The frequency of westerly and cyclonic systems remains relatively stable, with an insignificant decrease in cyclonic systems during the August–September bi-monthly period. The difference between the use of 3 and 10 day synoptic histories shows little variability, the main variation in percentage scores reflects the small number of events with associated synoptic conditions during the June–July period.

5 Discussion

5.1 AD 1600–1799

The period AD 1600–1799 presents evidence of some variability within flood seasonality; but the confidence that can be associated to this variability is uncertain (Table 2). Seasonality measurements for the seventeenth century are susceptible to considerable sensitivity as only nine flood events are recorded (23 events are recorded for the eighteenth century); as a result considerable up-scaling is undertaken during normalization. The apparent flood-rich period AD 1600–1650 (Fig. 2) previously identified by Macdonald and Black (2010) appears within the data, but has no significant impact on seasonality. The period AD 1720–1870 itself in the UK represents a longer period of warming following the LIA (Lamb 1995), with the early nineteenth century in Central Europe characterised by a cooler phase (Dobrovolný et al. 2010), though no notable influences on flood frequency/magnitude or seasonality are evident within the Yorkshire Ouse catchment. This contrasts to previous studies in Europe, the periods 1730–1790 and 1790–1840 are identified as having higher flood occurrence on Central European rivers (Glaser et al. 2010); whilst, Brázdil et al. (1999) identified that long-term changes in flood frequency can be correlated with the main periods of the Little Ice Age (LIA).

5.2 Summer floods

The high number of floods recorded during June–July in the 1800–1899 (before AD 1877) period may reflect notable river flows rather than flood magnitude (notable events that are recorded as being unusual for that season, but which are not actually an AM flood). The high frequency of summer events (JJA) within the early record compared to the later record is clearly illustrated in Fig. 3. The high number of August–September floods recorded during the AD 1700–1799 period, and records of several significant summer floods on the River Tyne (northeast England) in the 1760s and 1770s, resulting from localised intense precipitation (Archer 1992) suggest that summer flooding may have previously been more prominent. McEwen (2006) also noted an increased incidence of summer floods on the River Tay (Scotland), with 21% of floods recorded in the period 1865–1894 occurring during the summer months, compared to no AM floods within the summer months (June–August) during the gauged period.

5.3 Flood frequency variability

The absence of significant flood events (water level >10 m) and only 16 floods >9 m during the period AD 1831–1982 within the River Ouse catchment, suggests that land use changes are unlikely to have altered the catchment hydrology in a manner sufficient to increase flood magnitude or influence flood seasonality. The relative absence of notable flood events in the 1960s and 1970s (a period coinciding with rapid growth in the UK river gauging network) across the UK (Marsh and Hannaford 2007), compared to the relatively ‘flood rich’ recent past (last decade) may have contributed to a perception of increasing flood frequency and magnitude within recent years across the UK.

5.4 1800–1999 and flood generating mechanisms

The principal finding of this work has been the shift in flood seasonality within the period AD 1800–1999 from the December–January to the February–March bi-monthly period, particularly for high flows (Table 3; Figs. 3 and 4). Initially the principal explanation postulated was a reduced influence of snowmelt driven floods as a result of rising temperatures within the uplands of the Ouse catchment (Holden and Adamson 2002), but this is not supported by the AM series data. An alternative explanation maybe an increase in the frequency of North Atlantic storms, but a phase of increased North Atlantic storminess at the end of the nineteenth century identified by Dawson et al. (2002), does not correspond to any shift within flood seasonality records, consequently this also appears unlikely. The increase in late nineteenth century storminess is not identified by Hanna et al. (2008), nor do they determine a significant increase in recent decades in storm frequency or severity; whilst Alexander et al. (2005), noted that there is no significant relationship between North Atlantic Oscillation Index (NAOI) and North Atlantic storminess.

No variability in the generating mechanisms responsible for flood events over the period AD 1800–1999 has been determined; with the ratio of snowmelt and heavy rainfall generated flood events appearing relatively stationary. Changes in the frequency of winter floods has been attributed to increased winter temperatures (Brázdil et al. 2005), when studying the River Vltava (Czech Republic), though there is no evidence in this study to support similar findings within the Yorkshire Ouse catchment. The use of longer records (in this study 10-day) is of greater value in providing a better depiction of the synoptic conditions prior to flooding and in identifying the conditions which are liable to give rise to flood events (Jacobeit et al.

2006), including the potential for the accumulation and presence of snow within the catchment. The CETS record clearly identifies events where thaw is a contributing factor, but is unable to determine the proportion snowmelt contributes to any given flood. Therefore, the mechanisms responsible for the apparent increase in late winter flooding are still uncertain. The shift to a later flood seasonality identified within this paper is supported by the findings of McEwen (2006) in her analysis of the River Tay (Scotland) for the period 1948–1999, but with greater temporal and seasonal variability prior to this, based on documentary accounts. Analysis at multiple alternative sites with long records (prior to AD 1900) would help to clarify whether the pattern of later (February–March) flooding identified within this paper reflects a localised North England (and Scotland—McEwen 2006) anomaly within the flood records, or a wider reaching shift within Western Europe.

The Ouse catchment is a large system (within a UK perspective) where many of the factors contributing to flooding are buffered, Longfield and Macklin (1999) illustrate the challenges in attempting to attribute increases in flood frequency solely to changes in the catchment. Small upland catchments may more clearly reflect abrupt changes within the climate and subsequent flood frequency, potentially explaining the contrasting findings of this paper to Macklin and Rumsby (2007). This raises an interesting question of scale within catchment responses to climatic variability, with further analysis over longer timescales (late Holocene) required in both upland and lowland catchments assessing the temporal and spatial variability in flood frequency, magnitude and seasonality.

6 Conclusion

This paper presents a robust approach for considering augmented flood seasonality records from documentary and instrumental sources. It has demonstrated that variability in flood seasonality exists within the period AD 1600–1799, but the extent of that variability is unclear, a result of limited data availability. This paper has also demonstrated that there is considerable variability in flood seasonality since AD 1800 within AM flood records; with the period since AD 1950 witnessing a marked increase in flooding in the bi-monthly period February–March. The apparent increase in the number of February–March flood events may be a stochastic anomaly, or reflect a change within flood seasonality in the River Ouse catchment. The climatic generating mechanisms leading to flooding appear to have remained relatively stationary in the long-term (from AD 1800), with no notable change in the frequency of snowmelt generated floods. Of the flows since AD 1999 (2000–2006) five AM exceed the threshold, two of which are within the February–March period with one flow in December–January period and the remaining two flows in the August–September period (a period with few AM flows in previous periods). As no apparent change is identified in meteorological flood generating mechanisms, the shift observed in high-magnitude flood seasonality will require greater consideration to determine whether it represents a significant variation or a single regional anomaly.

Understanding the seasonality of flooding is important for a wide range of river based activities, from direct river management (e.g. water resource managers) to those working within the adjacent river environment (e.g. bridge maintenance). A better understanding of flood seasonality over the long-term will be important in reducing reliance on understandings based on short instrumental series (e.g.

Macdonald et al. 2010), which often fail to reflect long-term variability. Increasingly water managers are having to consider and plan for increased uncertainty within hydrological systems, coupled with greater demands of maintaining 'good ecological status' as set out within the Water Framework Directive (European Communities 2000), which will require a better understanding of hydrological variability (Petts et al. 2006).

This paper has illustrated the potential value of documentary records as a tool in developing a better understanding of long-term flood seasonality, and the mechanisms which generate high-magnitude flood events. An improved understanding of hydroclimatological variability under differing climatic conditions is of significant value when addressing the capability and likelihood of a catchment producing high magnitude floods. Further analysis is required of large catchments within Western and Central Europe to determine if the patterns identified in this paper represent a more widespread change during the last 50 years, if so this will have considerable significance in flood mitigation and water resource management across Europe.

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