Reassessing flood frequency for the River Trent through the inclusion of historical flood information since AD 1320

Neil Macdonald

ABSTRACT

The estimation of return periods for floods likely to have significant societal impact is challenging unless suitably long records exist. Relatively few sites across the UK provide a continuous record of river level or discharge over 50 years, whilst records extending back to the nineteenth century are rare. This represents a significant problem in providing robust and reliable estimates of flood risk, as relatively short records often fail to include an adequate sample of large floods. The inclusion of historical flood levels/magnitudes prior to instrumental river flow recording presents a valuable opportunity to extend this dataset. This paper examines the value of using historical data (both documentary and epigraphic) to augment existing gauged records for the River Trent in Central England, as part of a multi-method approach to assessing flood risk. Single station and pooled methods are compared with flood risk estimates based on an augmented historical series (1795–2008) using the generalised logistic and generalised Pareto distributions. The value of using an even longer, but less reliable, extended historical series (1320–2008) is also examined. It is recommended that modelling flood risk for return periods >100 years should incorporate historical data, where available, and that a multi-method approach increases confidence in flood risk estimates.

Key words | flood, flood frequency, historical, Nottingham, Trent

Neil Macdonald
School of Environmental Sciences,
The University of Liverpool,
Roxby Building,
Liverpool,
L69 7ZT,
UK
E-mail: *neil.macdonald@liv.ac.uk*

INTRODUCTION

The application of historical flood information when reassessing flood risk has increased during the last decade (Brázdil *et al.* 1999, 2006; Glaser & Stangl 2003; Böhm & Wetzel 2006; McEwen & Werritty 2007; Glaser *et al.* 2010; Herget & Meurs 2010; Elleder *et al.* 2013), with an increasing number of studies incorporating historical records when reassessing flood frequency analysis (Benito *et al.* 2004; Werritty *et al.* 2006; Macdonald & Black 2010). While the use of historical information within flood risk analysis has increased in recent decades, the concept and use of historical events is not new, as both Flood Studies Report (FSR) (IH 1975) and Potter (1978) encourage consideration of historical information in flood assessment. Within the UK the average gauged river record consists of about 35 years of data, with only a select number of sites exceeding 75 years in length (Marsh & Lees 2003). The limitations of data availability and rareness of extreme events within these records has resulted in an increased recognition in the potential value of historical flood records in better understanding the frequency of extreme events. This has received added prominence following a number of severely damaging flood events since the early 1990s within the UK (Marsh & Hannaford 2007; Hannaford & Marsh 2008) and mainland Europe (Kundzewicz *et al.* 1999; Szlávik 2003; Ulbrich *et al.* 2003; Bezzola & Hegg 2007; Schmutz *et al.* 2008). These events have heightened demands for better flood risk assessments, particularly for rare (extreme) events and also increased attention on the methods and data used for producing them.

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The City of Nottingham in Central England presents one of the longest flood histories within the UK, with a series of historical flood levels dating from 1852 inscribed into the abutment of Trent Bridge (Figure 1(a)), a series of annual flood levels at Trent Bridge from 1877 until 1969 and descriptive accounts from the thirteenth century. The wealth of records reflects the prominent role of the city as both a centre of trade and commerce, as a site of strategic military importance, and as an important bridging point.

This paper explores the benefits of additional information in the form of historical records being incorporated into flood frequency estimates. More specifically, the objectives of this paper are:

1. to examine the viability of incorporating historical information into flood frequency analysis;
2. to consider the sensitivity of the approaches available and suitability at Nottingham; and
3. to reassess flood risk at Nottingham using historically augmented datasets compared to conventional UK flood frequency analysis approaches.

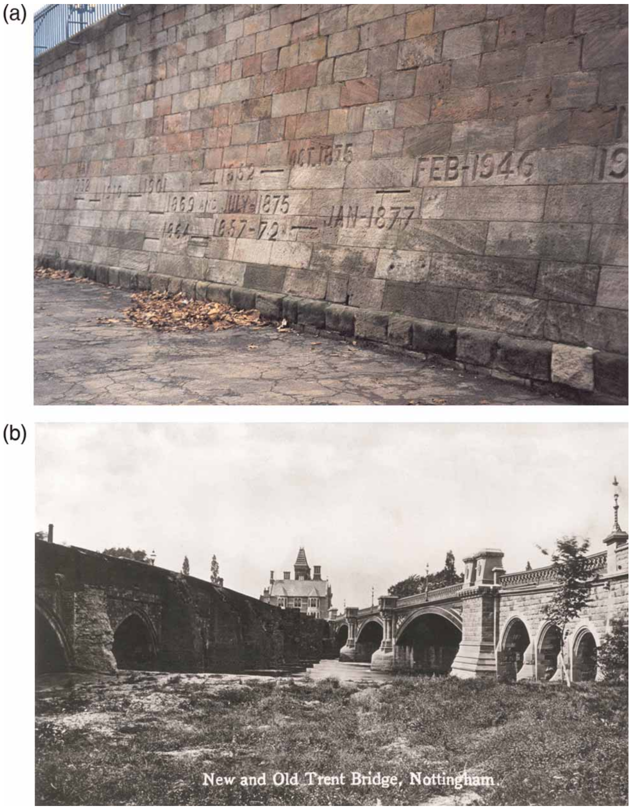

Figure 1 | (a) Epigraphic markings on Trent Bridge; (b) the Hethbeth Bridge (left) and Trent Bridge (right), *c.*1870 (Beckett 1997).

THE TRENT CATCHMENT

The River Trent has five major tributaries: the Tame, Soar, Ryton, Derwent and Dove (Figure 2), with a mean annual discharge of 84.3 $m^3 s^{-1}$ at Colwick (028009), approximately 5 km downstream of Nottingham (Marsh & Lees 2003). The Trent catchment upstream of Colwick gauging station is 7,486 km^2, stretching in the southwest to Birmingham, in the north to Howden Moor (near Glossop) and enters the River Humber Estuary to the northeast (Figure 2). The catchment lies predominantly beneath the 250 m contour (Hains & Horton 1969), except for a few areas in the Peak District near the source of the Rivers Derwent and Dove at over 450 m (Edwards & Trotter 1954). A diverse range of bedrock types are found which can be grouped into those found in the Peak District and at higher altitudes (Millstone Grit and Carboniferous Limestone), and those found in the lowland areas (superficial alluvial deposits, beneath which are red sandstones and historically significant Coal Measures). The Trent catchment land use is varied; to the north are hilly areas, which are predominantly rural, with forestry, pastoral and rough (sheep) grazing. Arable farming is the dominant land use in the lowland areas. There are considerable population centres within the Trent catchment, Birmingham located on the River Tame in the west of the catchment, Nottingham on the River Trent, Derby on the River Derwent and Leicester on the River Soar; providing a total urbanised coverage of around 11% for the catchment (Marsh & Hannaford 2008).

The distribution of precipitation within the Trent catchment is determined largely by elevation, with northern sections of the catchment (Peak District) receiving in excess of 1,000 mm a^{-1}, which falls to ~ 550 mm a^{-1} in the eastern areas (Kings & Giles 1997), with a catchment average of ~750 mm a^{-1}. The upper River Derwent contains three large reservoirs in the Peak District section, the reservoirs Derwent (holding *c.*9.5 Mm^3), Howden (holding *c.*9 Mm^3) and Ladybower (holding *c.*28.5 Mm^3) (Potter 1958). Their role in reducing the magnitude of flood peaks

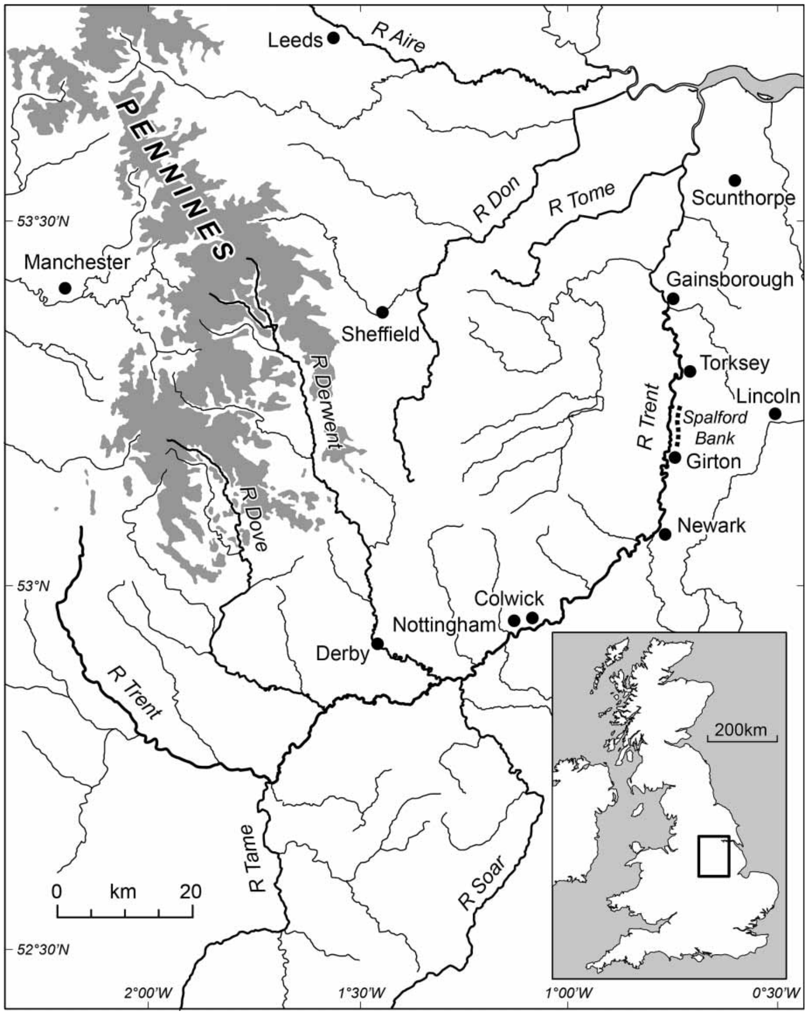

Figure 2 | The Trent catchment.

in the lower catchment at Nottingham is minor, as the proportion of the catchment controlled by these reservoirs at Colwick is only 1.7% (IH 1999).

DATA SOURCES, CALIBRATION AND HARMONISATION

An evaluation of the historical data is vital prior to any potential incorporation within flood frequency assessments. The individual records require assessment through the cross referencing of information from coeval sources where available. This can represent a problem for the oldest sources, but is valuable in identifying spurious events (Macdonald & Black 2010). In cases where heights have been attributed to an event, critical assessment of these levels and conversion of the levels into a discharge is required where possible; Table 1 contains all *known* recorded events with flood levels/heights at Nottingham, Table 2 contains all listed floods within the FSR (IH 1975) at Trent Bridge, based on stageboard readings (1884–1969, excluding 1956–1957). The identification of historical flood information can be time-consuming, but electronic databases such as the British Hydrological Society's Chronology of British Hydrological Events (CBHE) website (Black & Law 2004) provides a valuable tool in searching for historical hydrological information

Table 1 | The largest historical floods, and floods of *known* height at Nottingham from sources other than the Flood Studies Report (IH 1975), prior to the start of gauging at Colwick in 1958

Year	Day/ Month	Heights (mAOD) (various sources)	Peak flow estimate (cusec – cubic feet per second)	Inferred flows from sources ($m^3 s^{-1}$)	Cause	Source
1141						Potter (1964)
1254						Potter (1964)
1329		12.00		764		Trent River Board (1930)
1486		12.40		864		Trent River Board (1930)
1684	15/02	13.10		1,040	Thaw	Trent River Board (1930)
1697	12	12.60		915	Thaw	Trent River Board (1930)
1770	11	13.50		1,140		Annual Register (1770); Stark (1843); Padley (1882)
1795	2	14.60		1,415		Marriot & Gaster (1886); IH (1975); Trent Bridge
1852	11/11	13.42		1,119		Marriot & Gaster (1886); IH (1975); Trent Bridge
1857	13/08	11.43		666		Marriot & Gaster (1886); Trent Bridge
1864	3	11.18		625		Marriot & Gaster (1886); Trent Bridge
1869	19/12	12.50		879		Marriot & Gaster (1886); Trent Bridge
1872	16/12	11.50		679		Trent Bridge
1875	20/10	13.75		1,221	Rain	Marriot & Gaster (1886); IH (1975); Trent Bridge
1877	03/01	11.80		733		Trent Bridge
1886	15/05	12.70		926	Rain	Marriot & Gaster (1886)
1901	02/01	13.00		1,002	Rain	Trent Bridge
1909	25/12		25,700	728	Thaw	Met O (1968)
1910	04/12		32,620	926	Thaw	Trent Bridge
1912	28/08		25,800	731	Rain	Met O (1968)
1916	28/02		24,050	682	Thaw	Met O (1968)
1919	14/03		22,860	649	Rain	Met O (1968)
1923	28/02		20,310	572	Rain	Met O (1968)
1926	02/09		23,340	662	Rain	Met O (1968)
1927	24/11		27,580	781	Thaw	Met O (1968)
1928	25/11		21,460	609	Rain	Met O (1968); EA (1999)
1932		12.45		849		Trent Bridge; TRA (1966)
1946		12.94		1,000		Trent Bridge
1947	18/02	13.11		1,130		Trent Bridge; TRA (1966)

The Trent Bridge markings are those located on the southern bank of the Trent Bridge.
EA represents the Environment Agency.
Met O represents the Meteorological Office.
TRA represents the Trent River Authority.

quickly and efficiently. For this study numerous other independent source materials were examined, such as documentary records (e.g. *British Rainfall*), epigraphic records (Macdonald 2007 – Figure 1(a)), local and national newspapers and various other sources. Potter (1978) provides a comprehensive review, with further good examples

Table 2 | The largest floods listed within the Flood Studies Report (IH 1975), 1884–1969

Date	Discharge ($m^3 s^{-1}$)	Date	Discharge ($m^3 s^{-1}$)	Date	Discharge ($m^3 s^{-1}$)
19/12/1884	164	25/01/1913	360	26/01/1942	502
01/11/1885	484	19/12/1914	345	02/02/1943	453
15/05/1886	951	02/01/1915	565	22/11/1944	350
21/01/1887	867	04/03/1916	689	02/02/1945	561
29/12/1888	464	10/01/1917	394	09/02/1946	1,006
10/03/1889	823	20/01/1918	475	19/03/1947	1,107
25/11/1890	454	13/03/1919	643	14/01/1948	495
14/12/1891	538	12/01/1920	388	02/01/1949	624
16/10/1892	371	19/01/1921	394	11/02/1950	477
02/03/1893	216	22/12/1922	720	08/01/1951	624
15/11/1894	248	28/02/1923	579	21/12/1952	374
22/01/1895	787	04/06/1924	481	19/02/1953	319
29/12/1896	344	14/02/1925	358	15/12/1954	350
07/02/1897	802	09/02/1926	658	27/03/1955	747
23/08/1898	276	24/12/1927	388	1958	N/A
22/01/1899	325	25/01/1928	600	1957	N/A
08/01/1900	516	11/12/1929	512	05/10/1958	311
01/01/1901	967	16/01/1930	421	23/01/1959	547
02/01/1902	595	06/09/1931	506	05/12/1960	810
29/10/1903	527	23/05/1932	945	06/02/1961	326
10/02/1904	511	01/03/1933	704	21/12/1962	268
15/03/1905	119	30/12/1934	228	06/03/1963	296
09/01/1906	368	24/12/1935	708	15/03/1964	356
15/12/1907	493	31/01/1936	388	11/12/1965	731
05/05/1908	493	19/03/1937	407	21/03/1966	570
24/12/1909	720	27/11/1938	239	28/02/1967	376
03/12/1910	908	09/01/1939	646	15/01/1968	468
16/12/1911	329	24/02/1940	780	21/01/1969	394
28/08/1912	681	10/02/1941	624		

of the potential source materials available provided by Brázdil *et al.* (1999), McEwen (1987) and Williams & Archer (2002).

Sources such as the Trent River Board (1930) and Potter (1958, 1964, 1978) suggest that the largest event with a 'known' level is that of 1795. The numerous descriptions endorse the extreme nature of the flood, but assessing the validity of the estimated height attributed to it is more complex. The level frequently used for the 1795 flood appears to have originally been provided by Marriot & Gaster (1886); 91 years after its occurrence. Although a considerable time period, this does not indicate that the estimate should be removed or discarded without consideration, particularly when reviewed within the context of estimates provided for subsequent floods of comparable magnitude. It is quite possible that markings and levels were made after the 1795 event and that these markers were used in determining the flood level estimated by Marriot & Gaster (1886). These markings may subsequently have been lost. The 1795 event is recorded by Stark (1843), but without any height, extent or level indications, although containing potentially important information concerning the generating mechanisms. The description by Padley (1882) in which he describes the level of the 1770 event as being 13 inches lower than that of 1795 at Newark (see Figure 2) provides a useful cross-reference and shows that an awareness of the 1770 and 1795 event was retained, though how this level difference was derived is unknown.

The floods of 1852 and 1875 represent a change in the quality and quantity of recording. The flood of 1852 is the first event to be marked onto Trent Bridge, and is corroborated with newspaper reports documenting the flood (Leicester Chronicle 1852). Subsequent floods are well recorded in numerous sources (Trent Bridge; Annual Register 1852; Marriot & Gaster 1886; Trent River Board 1930; Nixon 1960; IH 1975), though it is quite probable that later sources relied upon earlier sources for descriptions of older events (see Table 1). The increased number of documentary sources available for the floods of the nineteenth century increases the level of confidence as these descriptions permit cross-referencing. Considerably more information is available for the 1875 event and subsequent events, as a result of increased documented sources and improved newspaper coverage.

Table 3 identifies the 20 largest events that are recorded for the Trent at Nottingham. Inclusion of records from before AD 1770 (1329, 1486, 1684 and 1697) introduces uncertainty, as differing heights are reported in many accounts, but all appear to be derived from a single descriptive source; multiple sources rarely exist for the oldest records. As a result, flood events prior to that of 1795 are considered to have a greater degree of unreliability in their flow estimates/descriptions. The events of 1770 and 1795 are well documented, the latter particularly well for an event during this period. As a result, analysis has been conducted for all events from 1795 onwards, a timeframe comparable to that selected in previous studies (Macdonald *et al.* 2006; Macdonald & Black 2010), which undertook analysis from 1800 onwards. The use of a shorter timeframe provides greater reliability and confidence in the recent records (Parent & Bernier 2003). The apparent improvement in the quality of records after 1795, combined with the provision of flood levels (on Trent Bridge) has led to the assumption that the heights described are accurate and are therefore used within this analysis, though an assessment of each flood level/description was conducted. Although not all the data have been included in the initial analysis (only post-1795), they are assessed later within the paper to provide an evaluation of the role additional historical flood event inclusion can have.

Table 3 | The 20 largest ranked floods at Nottingham

Rank	Date	Discharge ($m^3 s^{-1}$)	Rank	Date	Discharge ($m^3 s^{-1}$)
1	1795	1,415	11	1886	951
2	1875	1,274	12	1932	945
3	1770	1,140	13	1697	915
4	1852	1,133	14	1910	908
5	1947	1,107	15	1869	889
6	1684	1,040	16	1887	867
7	2000	1,019	17	1486	864
8	1946	1,006	18	1889	823
9	1901	967	19	1960	810
10	1977	957	20	1897	802

Harmonisation of data from the various sources is required prior to the augmentation of the historical data and the gauged series. At Nottingham, five types of record are present:

1. Discharges from Colwick gauging station in $m^3 s^{-1}$ (1958–present).
2. A compiled series from the FSR (IH 1975) of annual maximum flood levels recorded at Trent Bridge from 1884–1955 and 1958–1969, with rated discharges.
3. Peak stage records in feet and inches above Ordnance Datum at Trent Bridge, intermittent since 1852.
4. Peak stage above summer level values in Nottingham (intermittent since 1795).
5. Estimated peak flows from the early twentieth century (estimated in cusecs) (intermittent during the period 1909–1955).

Many of the oldest floods were attributed heights by the Trent River Board in the 1930s and are probably derived from older sources (such as Marriot & Gaster 1886) or from estimates based on research at the time. Subsequent works have often accepted these heights, e.g. Environment Agency (1999). In combining data from each of these sources, the data require harmonisation. The series contained within the FSR (IH 1975) from 1884 to 1969 (1956–1957 missing), is based on four separate series and subsequent ratings made at Trent Bridge. Theoretically, the data from sources (4) and (5) should be readily comparable as both are recorded from adjacent locations for some of the same events (Figure 3(a)). The data in (5) are flows in cusecs (cubic feet per second), a measurement used prior to metrification in the UK, as these events overlap with those of (2) they are used for cross-checking and provide increased confidence in the existing record. The data in (1) are already in the required form, but are important in calculating the rating curves, whilst data in (2) are already calibrated to a discharge, though for Trent Bridge. The use of the rating curves (Figure 3) allows comparison of flood peak values obtained from different sources, giving an indication of potential recording error, and permits the conversion of the historically recorded heights and volumes in their various forms to be converted into discharge estimates ($m^3\ s^{-1}$), permitting augmentation with gauged data. Figure 3(a) plots the floods recorded as above Ordnance

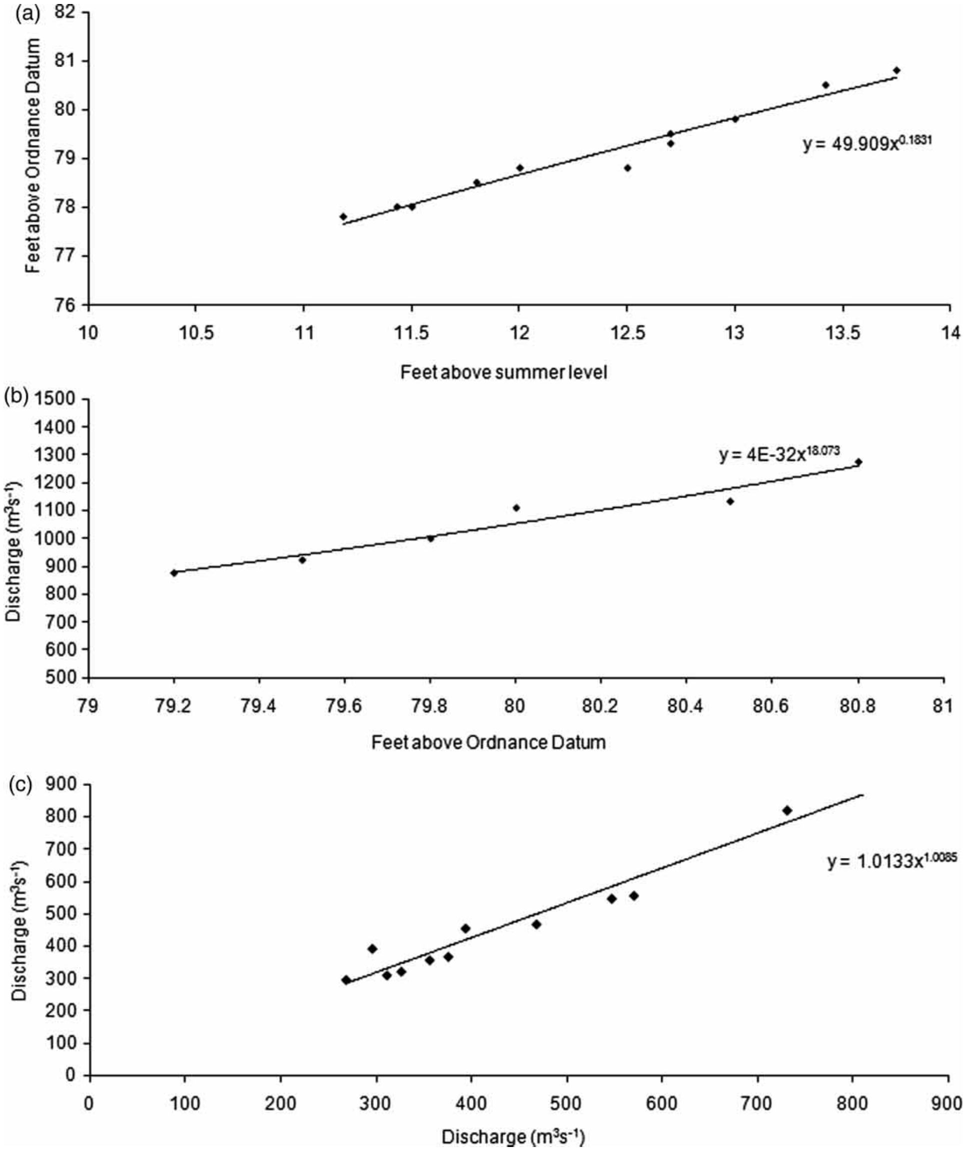

Figure 3 | (a) Rating curve: comparison of above Ordnance Datum and above summer level (feet) data. (b) Rating curve: comparison of feet above Ordnance Datum and discharge ($m^3\ s^{-1}$) data. (c) Rating curve: comparison of the Trent Bridge record from the FSR (IH 1975) and Colwick gauging station for the overlapping period 1958–1969.

Datum (AOD) against those recorded as above Summer Level (SL) near to the current Trent Bridge site, recorded in feet and inches (1852–1901) (a simple conversion is possible based on the mAOD at the site *c.*20 m (*c.*65 ft.), graphical analysis permits any potential recording error to be identified). Figure 3(b) shows the relationship between mAOD and discharge ($m^3 s^{-1}$), permitting conversion of the historic flood levels recorded as either AOD or harmonised SL (using the rating curve in Figure 3(a)) into a discharge ($m^3 s^{-1}$). The cusec (cubic feet per second) values are harmonised by division of their flows by the constant (35.135). The relationships between the variables are strong with R^2 values (coefficient of determination) all above 0.96. The final rating curve illustrates the close relationship between Trent Bridge and Colwick gauging station annual maximum flood records for the overlapping period, 1958–1969.

Inevitably the changing channel form throughout the historical period represents a challenge when estimating historical flows, hence within the paper, two periods are considered, the shorter (1795–2008) represents a period of greater reliability, the longer (1320–2008) a period of greater uncertainty in flood estimates and comparability of flood generating mechanisms. Within this paper estimates are derived using a single stage-discharge relationship, as previous work (Macdonald & Black 2010) has suggested that at the largest flows, minor changes within the channel and catchment may have minimal impact on flood discharge.

HISTORY OF NOTTINGHAM

The name Trent is of Anglo-Saxon origin and is possibly derived from an old name 'Trisantona', meaning trespasser – a reference to the frequent flooding of the river onto the floodplain in historical times (Large & Prach 1998). The growth of the city of Nottingham starts around AD 920 when it became a centre for royal administration. Archaeological evidence suggests that there was a thriving medieval town by the turn of the eleventh century, with the construction of the castle by AD 1068. It is around this point that the River Trent occupied its current position, with the previous channel being located to the north of its current location (Snell & Galloway 1926). As with many medieval cities, Nottingham had a wall around the town from the thirteenth to sixteenth centuries. A great deal is known concerning the activity of the borough of Nottingham; the city has a unique series of scrolls documenting the period AD 1303–1455. These scrolls highlight the importance of the River Trent to the prosperity and trade activities during the medieval period. By the sixteenth and seventeenth centuries, Nottingham represented a typical country town (the city charter was granted in 1897), with the earliest map being the crown survey of Sherwood Forest in 1609. The first map of the town of Nottingham dates from 1610 (drawn by John Speed) and illustrates the city walls, but that little expansion had occurred. The subsequent map of 1675 by Richard Hall shows that the medieval walls were still in place, but that expansion and development was occurring within them; the map produced by Badder and Peat of 1744 shows the town expanding outside its medieval walls. The eighteenth century represents a phase of significant change, as the town expanded rapidly and industrialised. There are two prominent maps from the nineteenth century prior to the start of the Ordnance Survey; Sanderson's map of 1835 and Drearden's map of 1844, which clearly identify the industrial expansion and the movement away from the confined city seen in previous maps. The planform of the River Trent in the latter two maps indicates stability within the channel, post *c.*1800, with industrial development along the northern bank, in the area historically known as 'the meadows' (copies of all the maps discussed can be seen in Beckett (1997)).

HISTORICAL FLOODS OF NOTTINGHAM

Floods are recorded throughout the history of Nottingham, with the earliest dating from AD 1254 (Potter 1958, 1964), though little is known about the magnitude and impact of the event. The information detailing the historical floods at Nottingham can be attributed to many sources; Table 1 contains a summary of the largest historical floods and those that have been estimated prior to the start of the gauged record in 1958. The principal sources for historical flood information identified for Nottingham are *British Rainfall* (1860–1991), the *Annual Register* (1758–2001), local newspapers, Trent River Board reports and Marriot & Gaster (1886).

These floods and associated heights can be cross-referenced where possible to epigraphic markings on Trent Bridge (Figure 1(a)); many of the markings show levels extracted from the bridge prior to renovation in 1987, or those transferred from the old Hethbeth bridge (Figure 1(b)) at the end of the nineteenth century. The markings were carefully inscribed (resurveyed) and correlate closely with those described by Marriot & Gaster (1886). The close relationship between the heights is an indication of their reliability and completeness; as with any catchment there are potential hydrological changes during the years following the first recorded flood, though the flood generating mechanisms are likely to be comparatively similar.

CHANNEL MANAGEMENT

The River Trent has some of the oldest channel management in the UK, with the banking of several breaches in a series of sand dunes (Spalford Bank) between Girton in Nottinghamshire (15 km upstream of Torksey) through to Marton Cliff, in Lincolnshire (Figure 2) (Padley 1882). When breached, the floodwaters can travel into the Witham Valley, the city of Lincoln and subsequently into the Fens causing substantial damage; a detailed description of this occurring during the 1795 flood can be found in the *The Lincoln Times* (Padley 1858). Floods breaking through the defences of the Spalford Bank can be used as broadly indicative of flood magnitude, as breaching of Spalford Bank occurs at discharges of *c.*1,000 $m^3 s^{-1}$ (Brown *et al.* 2001).

The management of the channel at Colwick can be dated back to the sixteenth century with carbon dates of a ‘kidweir’ (a line of posts with brushwood and wattle), which was used to strengthen the riverbank (Lord & Sailsbury 1997). Brown *et al.* (2001) also identify evidence of dredging within the channel, permitting coal barges to pass during the sixteenth century. A Parliamentary Act of 1783 authorised channel improvements from King’s Mill in Leicestershire through to Gainsborough in Lincolnshire (nearing the Humber Estuary). This signalled the intensification of navigation within the Lower and Middle Trent. Sailsbury (1992) identifies that prior to the intensification the reach of the channel between Nottingham and Newark was highly mobile and prone to avulse and meander, as evidenced elsewhere upstream, with significant channel migrations within the floodplain during the last 1,000 years (see Sailsbury 1992; Brown *et al.* 2001; Howard *et al.* 2008). During the late eighteenth and nineteenth century, Nottingham developed rapidly as an industrial centre, this resulted in the construction of the Nottingham Canal running from the River Trent to the town centre in 1793, which increased industrial development, growth in trade and transport along its length. In 1796 another canal (the Beeston cut) extended the Nottingham Canal to Beeston (Beckett 1997). The construction of these canals and the navigable depth of the Trent produced an intensely industrialised area with strong trade and manufacturing links.

HISTORY OF NOTTINGHAMS BRIDGES

The history of bridges in the Nottingham area is well documented by Brown *et al.* (2001) in which archaeological and sedimentological records combined with documentary sources provide a detailed chronology of bridge destruction and subsequent reconstruction. The earliest bridge lost to flooding is believed to have been destroyed around AD 1141 and was originally built in AD 924 at the bequest of Edward the Alder, Alfred the Great’s son (Whatnall 1928). This interpretation supports estimates by Beckett (1997) who, using archaeological records, suggested a building date of AD *c.*920. The replacement bridge is believed to have been lost in the AD 1254 flood or the flood of AD 1279 (Brown *et al.* 2001). The third bridge appears to have been lost in the early fourteenth century according to carbon dates and pollen analysis (Brown *et al.* 2001); potentially acting as a means of validation, as a large flood event is recorded in AD 1329 (Trent River Board 1930). The bridge constructed after the AD 1402 flood was the first to be constructed from stone and was located at the same site as previous bridges and was known as the Hethbeth Bridge (Figure 1(a)). The current Trent Bridge has stood at the site since 1870 and was refurbished in 1987 leading to the re-facing of the flood marks (Figure 1(b)). The old (Hethbeth) bridge was finally removed from the river channel after 1870, though part of the bridge remains on the south bank.

THE LARGEST HISTORICAL FLOODS AT NOTTINGHAM

The first recorded floods are those identified by Potter (1964) as occurring in AD 1141 and 1254. Floods in AD 1329 and 1486 are recorded, but little detail is provided, though the Trent River Board (1930) attributes a height of 12 and 12.4 mAOD respectively to these events, with no indication as to how these estimates were attained. The Trent River Board (1930) describes the event of 1486:

> 'It is known that the River Trent was frozen near Nottingham in the winter of 1485/86, and with the thaw the Newark Bridge was swept away' (*c.*25 km downstream of Nottingham).

The flood of 1684 identifies the importance of thawing as a flood generating mechanism as William Sampson, the Rector of Clayworth (5 km from Gainsborough (Figure 2)), recorded (in Trent River Board 1930):

> 'In this part of the lower valley of the River Idle … the frost began on 13th December, 1683, and with but two slight thaws lasted until 5th February. When the final thaw did come he records that the Nottingham and Muskham Bridges were beaten down by ice' (Trent River Board 1930).

Interestingly, this contradicts the history of the bridges in Nottingham, as it is known that the Hethbeth Bridge had stood on the site since AD 1402, suggesting that there may have been several bridges in Nottingham, or that the Hethbeth Bridge was damaged and subsequently repaired. Sampson also records the flood of 1697 on the River Trent at Gainsborough:

> '… ran against ye upper part of trees growing on Saundby Marsh bank [5 km upstream of Gainsborough] and cut some of the trees off. Further downstream the riverbank at Morton [5 km downstream of Gainsborough] gave way, and on the other side of the river the banks of Bycarsdyke and Dicken dike were also breached. It was fortunate that succeeding this rapid thaw there were several days of very fine weather. On 28th December however, it began to freeze again and on the following day as much snow fell as before so that we are exceeding fearful at another great thaw and deluge. This winter continued with severity well into May [1698]' (Trent River Board 1930).

The floods of 1770 and 1795 represent two of the largest on record. The flood of 1770 is described by Stark (1843) as:

> 'It began on 20th November when the floodbank between Laneham and Torksey broke. Floodwaters ran over the lock gates at Torksey, spreading east to Lincoln and the inhabitants of villages like Torksey and Saxilby (5 km east of Torksey) had to live in their upper rooms. The Trent floodwaters, joining those of the Witham at Lincoln, nearly destroyed both the High and Thorne Bridges there. The riverbanks were breached between Morton and Walkerith [near Gainsborough], this time in two places. At West Stockwith the banks of Bycarsdyke were breached and the flood laid all that country, the Isle of Axholme and all the lands to Thorne… under water, and great numbers of cattle, etc. were drowned.'

With Padley (1882) providing a comparison between the flood of 1770 and 1795, 'Trent flood [1770] which was lower than that of 1795 by 13 inches at Newark and 6 inches at Torksey.' The 1795 event is the largest flood with a recorded magnitude, to affect Nottingham (Table 1), an estimate of the level is provided by Marriot & Gaster (1886) of 14.60 ft. above summer level (est.); a detailed description is provided by Stark (1843) in Nixon (1960):

> 'The most severe flood of the 18th Century was that of 1795. Once again it was the result of the break-up of a severe winter. The frost lasted from 24th December 1794 until 9th February 1795. The River Trent froze so that from the middle of January to the time of the thaw no vessels were able either to arrive at or leave Gainsborough. The thaw began on 9th February and in the ensuing week considerable rainfall in the upper catchment area was added to the already swollen river. …Once again the Morton bank gave way and Spalford bank (see section 6.1.6 for a description of the banks along the River Trent) also breached [15 km upstream of Torksey]. As in 1770 flood waters spread eastwards to Lincoln, covering at its maximum extent some 20,000 acres, the depth of water in some places being as much as 10 feet. Once more the lower

> parts of Saxilby were flooded, as were those of Fenton, Kettlethorpe, Brampton [within 5 km of Torksey] and Torksey.'

The flood of 1852 was recorded by the Leicester Chronicle (1852) and Nixon (1960) respectively as:

> 'Nottingham (13th November) The town and neighbourhood were visited by one of the greatest floods ever remembered – more extensive than even the great floods of 1831 or 1834.… At the village of Wilford a great amount of damage has been done and a number of sheep lost. At Chilwell, a farmer lost 100 sheep. At Sawley the property destroyed is enormous. At West Bridgeford the water was never known so high since 1796 [sic]. At Adbolton, Colwick, Shenton, Clifton, Beeston [settlements around Nottingham] and other villages a great amount of damage has been done.… In the November 1852 flood the Trent rose rapidly on the 14th and by the early morning of the 15th was just coming over the top of the Spalford bank [see Figure 2] when the bank at Dunham, on the other side of the river which had been completed in 1844, breached over a length of 50 yards. In the village water was 9 ft deep in places and the population marooned in their upper rooms.'

The flood of 1875 is recorded extensively across much of the catchment. British Rainfall (1875) records the event at Nottingham:

> '…but in October, not only was the July flood exceeded, but that of 1852 also, and the flood of October, 1875, appears to have been the greatest flood since 1795.'

The estimation of the oldest floods, particularly those of AD 1329, 1486, 1684 and 1697, are questionable as the original sources for these estimates are unidentifiable.

DATA ANALYSIS

The assessment of flood frequency at Nottingham uses four approaches:

1. A single site analysis based on the gauged river flow record from Colwick gauging station, fitting a generalised logistic distribution by L-moments within the WINFAP-FEH software.
2. Pooled analysis consistent with UK common practice and guidance provided by Kjeldsen & Jones (2009), using a generalised logistic distribution fitted by L-moments within the WINFAP-FEH software.
3. A historically augmented dataset analysed using the Bayliss and Reed method, for two timeframes 1329–2008 and 1795–2008.
4. A generalised Pareto distribution (GPD) fitted by probability weighted moments, applied to data exceeding a threshold.

The single site and pooled curves in Figure 4 are placed on the same graph as the augmented series, though the single site flood curve can only be directly read from the return frequency and Q/QMED axis (discharge/median discharge).

Conventional flood frequency analysis

The single site and pooling approaches are both methods widely used within the UK for flood frequency analysis. The single site analysis using the gauged river record (1958–2008) provided by Colwick gauging station (National River Flow Archive Number: 028009), which is sited 5 km downstream of Nottingham (Figure 2). Notably the gauged record contains little information regarding flows above 500 $m^3 s^{-1}$ (as few events have occurred); of the 60 annual maxima, only 13 are above this threshold; highlighting the difficulty in reliable estimation of low probability floods using just the gauged Annual Maximum (AM) series (1958–2008). The pooling group was constructed within the WINFAP-FEH software, consisting of 1405 years of data, which is based on the FEH 5T (five times the combined record length) rule (Robson & Reed 1999), which provides a target estimate up to a return frequency of 250 years.

Historically augmented analysis

The gauged data were augmented with historical data using the approach outlined by Bayliss & Reed (2001). The augmented series is analysed using a threshold following the criterion that the threshold has a lower constraint determined by the lowest historical flood (Bayliss & Reed 2001),

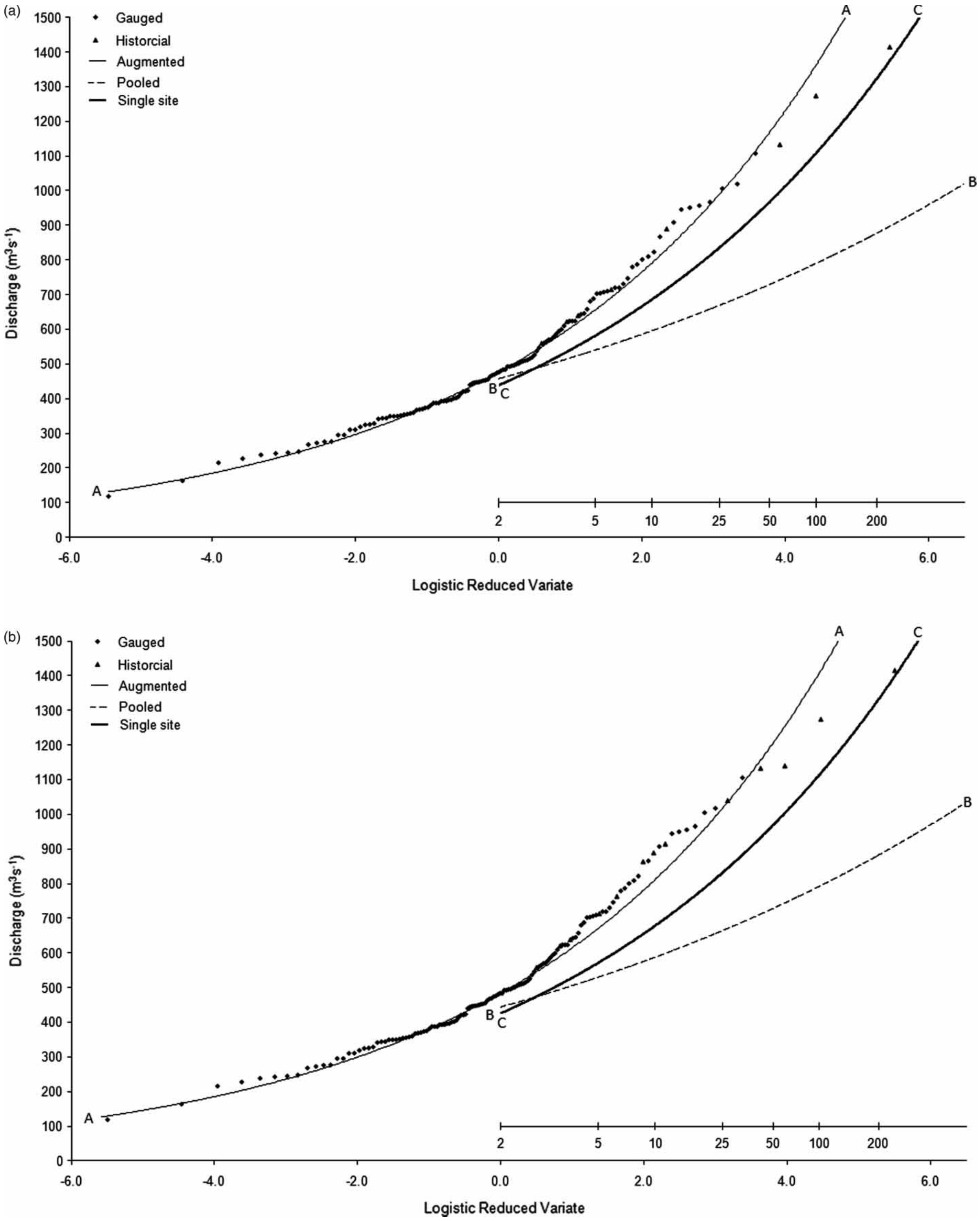

Figure 4 | Observed floods from historical and gauged records with curve fitted to combined data set using Bayliss & Reed (2001) method. Results of pooling and single-site analyses (1958–2008) plotted for comparison, relating to return period scale only. (a) 1795–2008 (QMED: 496.3); (b) 1320–2008 (QMED: 514.2). The return period is presented in years.

unless this is less than an event within the stageboard/gauged Peak over Threshold (POT) series, which is not an AM event. If this occurs then the threshold is increased to a point exceeding the largest event in the POT series that is not included within the AM series. This satisfies the assumption that all historical floods above this level are known. In this case the flood of 31st January 1960 (732.8 $m^3 s^{-1}$) is greater than the smallest historical flood, but is not included in the AM series (the largest event occurred on the 5th December 1960–810 $m^3 s^{-1}$), therefore the threshold is raised to 733 $m^3 s^{-1}$ to exceed the flood of 31st January 1960 (732.8 $m^3 s^{-1}$). The data are plotted using the equations identified in the Bayliss & Reed (2001) report, which permit all the data to be plotted together. The augmented curve fits the central group of data reasonably (Figure 4).

The GPD approach assumes a Poisson arrival rate of events (Wang 1991) and the use of a sufficiently high threshold so that Pickand's asymptotic theorem applies (Pickand 1975) to a series of independent randomly occurring flood peaks derived from the POT series (Parent & Bernier 2003). The consequence of the high threshold is the removal of the smaller events, resulting in the shape of the curve being derived from only the largest floods. The threshold of the smallest historical flood in the period 1795–2000 is used unless this fails the criteria identified above. In this case it does, therefore, the threshold is raised to 733 $m^3 s^{-1}$. The high threshold GPD provides a strong graphical fit to the data in the upper curve, with return frequency estimates smaller than those provided by the conventional methods (Figure 5 and Table 4).

RESULTS

Multi-method comparison

The curves derived from the different methods of analysis are plotted onto three graphs (Figures 4(a) and (b) and 5(a)–(d)). Figure 4(a) contains an augmented curve derived from data since 1795–2008, alongside the pooled and single site curves; Figure 4(b) contains an augmented curve derived from all historical data, 1320–2008, alongside the pooled and single site curves. The use of the constrained dataset (1795–2008) provides a potentially more reliable dataset than that of 1320–2000 (Figure 4), as greater confidence can be placed in the flood levels since 1795 (Macdonald *et al.* 2006).

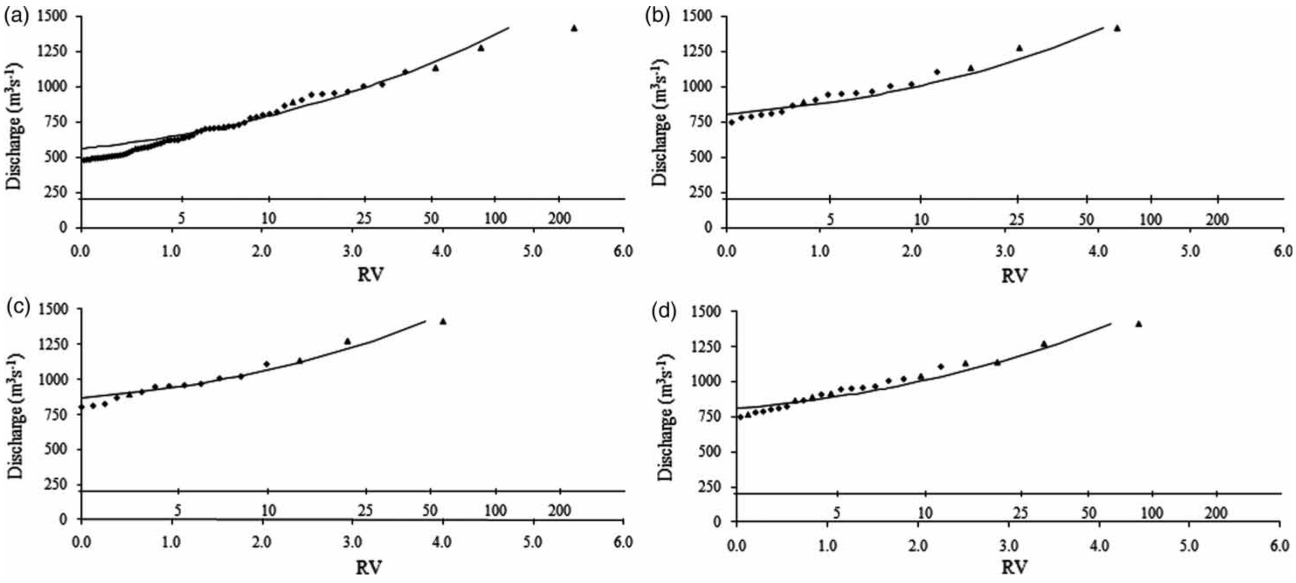

Figure 5 | Response of the generalised Pareto distribution based on changes in the threshold: (a) represents a threshold of 480 $m^3 s^{-1}$ (using the complete augmented record, 1795–2008, but violating the assumption); (b) shows the results if the threshold is set following the criteria to 733 $m^3 s^{-1}$ (conforming to the threshold requirements) (1795–2008); (c) illustrates the result of a raised threshold 800 $m^3 s^{-1}$ (reduced dataset) (1795–2008); (d) identifies the result on the curve if the complete historical record (1320–2008) is included in the analysis, again using a threshold of 733 $m^3 s^{-1}$.

Table 4 | The return period estimates for the single site, pooled, augmented and generalised Pareto curves in Figures 4(a) and 5(b)

Return period	Annual exceedence probability	Augmented curve (A–A) (1795–2008) ($m^3 s^{-1}$)	Pooled curve (B–B) (see Figure 4(a)) ($m^3 s^{-1}$)	Gen. Pareto curve (C–C) (1795–2008) ($m^3 s^{-1}$)	Single site curve (D–D) (1958–2008) ($m^3 s^{-1}$)
2	0.5	477	444	802	426
5	0.2	657	537	946	574
10	0.1	791	599	1,066	685
25	0.04	991	680	1,258	850
50	0.02	1,169	745	1,427	993
100	0.01	1,386	814	1,643	1,161
200	0.005	1,699	888	1,908	1,354
500	0.002	2,371	993	2,340	1,660

The discrepancy between the gauged, augmented and pooled curves is greatest for the high magnitude–low probability events (Table 4). The return frequency estimate for the 2000 event (1,019 $m^3 s^{-1}$) using the augmented curve is 28.2 years (1795–2008 – Figure 4(a)) compared to 25.1 years in Figure 4(b) (using the complete historical record, 1320–2008), while the pooled data estimate is >500 years – a considerable difference. The largest recorded flood, 1795 (1,415 $m^3 s^{-1}$), produces return period estimates of 102 years (Figure 4(b); 1320–2008) and 116 years (Figure 4(a); 1795–2008) using the augmented curves, while the pooled estimate is unrealistic with an estimate in excess of 5,000 years. The estimate from the GPD for the 1795 event is 60 years (Figure 5(b)). A possible explanation for the difference between the augmented and the pooled estimates for the 1795 event may be the construction of the pooling group, as the Trent catchment is considered as moderately urbanised (URBEXT2000 = 0.1050) the pooling group is generated on the average value of L-CV across all sites in the group, rather than using a weighted approach (as used in rural catchments), in which the 'at site' record at Colwick is given greater weight. The result is a pooling group consisting of sites with much smaller catchments and few records of high magnitude floods; as such, comparisons to the pooling group should be made with care.

The period 1795–2008 should be used in preference to that of 1320–2008, as a result of the greater reliability in records, and a catchment which exhibits characteristics more comparable to the present day, although it is acknowledged that human intervention over the last 200 years has changed the catchment. This does not indicate that the data pre-1795 should be ignored, but should possibly be considered apart from the post-1795, as a result of the potential for stationarity assumption weakness with older data.

Implications of the generalised Pareto distribution threshold location

The location of the perceived threshold when using a GPD has a lower constraint, which is determined by the presence of no other event within any given year exceeding the perceived threshold, except the annual maximum event. If this is below the level of the smallest historical flow, then this level is taken to satisfy the assumption that all historical floods above this level are known. There is no upper boundary to the threshold. Figure 5 identifies that the curve produced from the GPD flattens at the lower probability levels as the threshold is raised (Figure 5(a)–(d)). The use of a threshold requires careful consideration though, as shown in Figure 5(c), where the threshold (800 $m^3 s^{-1}$) has been raised to include only a small number of points. Therefore, it would appear appropriate, considering Figure 5, to retain the threshold used within the initial analysis (733 $m^3 s^{-1}$).

REGIONAL FLOOD GENERATING SYNOPTIC PATTERNS AT NOTTINGHAM

This section examines the synoptic conditions prior to the largest recorded flood events, and the potential value of the Central England Temperature (CET) in identifying thaw-generated floods. The data from the CET series

Table 5 | Synoptic conditions associated with the ten largest historical floods since 1861

Date	Estimate of peak discharge ($m^3 s^{-1}$)	Synoptic weather types for three days previous and day of flood	Temperature records for three days previous and day of flood (°C)
20/10/1875	1,274	Cyclonic Easterly, South Easterly, Easterly, South Easterly	9.6, 9.2, 10.6, 10.8
19/02/1947	1,110	Easterly, Easterly, Easterly, Anti-cyclonic Easterly	−1.8, −2.9, −3.1, −3.1
08/11/2000	1,019	Cyclonic Northerly, Cyclonic, Cyclonic, Westerly	7.7, 8.8, 7.1, 5.4
02/01/1901	1,015	Westerly, Cyclonic Westerly, ––––, Cyclonic	4.5, 4.1, 5.4, 4.6
23/05/1946	1,000	Anti-cyclonic, Southerly, Cyclonic, Cyclonic Easterly,	12.3, 11.4, 11.5, 11.3
05/12/1960	972	Cyclonic Westerly, Westerly, Westerly, Westerly	5.4, 8.8, 84, 8.1
26/02/1977	957	Anti-cyclonic, North Easterly, Easterly, Cyclonic	2.0, 3.8, 4.8, 6.4
15/02/1886	940	Northerly, Cyclonic Northerly, Cyclonic North Easterly, Cyclonic	6.6, 7.0, 6.6, 7.0
09/12/1910	924	Cyclonic Southerly, Cyclonic South Easterly, Southerly, Cyclonic South Westerly	8.7, 7.9, 7.5, 8.1
19/12/1869	889	Westerly, Westerly, Westerly, Cyclonic	6.6, 8.3, 7.2, 7.0

Weather patterns identified from Lamb (1972) and CRU (2001). Temperatures from the British Atmospheric Data Centre website: BADC (2001).

included in Table 5 provide an indication of climatic conditions prior to known floods. This information is assessed in an attempt to identify a proxy method for the validation of thaw occurrence within the historical flood records (Table 1).

Due to the size of the Trent catchment (in excess of 7,000 km^2), it is possible for flooding to occur in parts of the catchment, while other parts remain unaffected. Individual tributaries of the Trent may flood without having serious consequences at Nottingham. Synoptic conditions prior to known flooding events are considered; due to the size of the catchment a lag of 12–16 h can be anticipated between the catchment headwaters and Nottingham (Environment Agency 2002), providing valuable time in flood management provision. Table 5 identifies the synoptic conditions for the 3 days prior to known recorded flood events. Analysis of the synoptic conditions for the largest ten floods since 1861 (Table 5) (1861 is the start of the weather classification) identifies that the most frequently occurring mechanisms for flooding in the Trent catchment appear to be:

- Cyclonic; four events.
- Westerly; three events.
- Easterly; three events.

Of those events with thaws as the generating mechanisms in the documentary accounts, two had predominantly Easterly conditions, while Cyclonic and Westerly conditions can be attributed once each to snowmelt generated events. Snowmelt/thaw appears to cause four of the largest events; those of 1869, 1910, 1947 and 1977. Of these the CET series shows that only 1947 and 1977 were preceded by sub-zero daily temperatures at Nottingham (3 days prior to the flood, Table 5). Low temperatures in the extended record (previous 14 days) identify that low temperatures preceded the floods of 1795, 1927 and 1982 and may have permitted snow accumulation. Although no weather type analysis is possible for the flood of 1795, the temperature series supports the concept of a thaw flood, as prior to the 9th February (the day of the flood) the temperature record suggests a period of rapid warming (−4.5, 1.2, 4.7 and 5.6 °C). A more complete analysis of spatial variations in snow accumulation and rates of warming are needed, the study by Macdonald (2012) examines the River Ouse catchment (a similar sized catchment to the north of the River Trent) and identifies that there appears to have been no change in flood generating mechanisms, particularly the role of thaw during the last 200 years, though this remains difficult to characterise in upland areas. The historical descriptions of the floods indicate that throughout the record only five floods are described as notable for ice-floes, AD 1485, 1621, 1683, 1795 and 1814, with only the floods of 1485 and 1683 responsible for bridge collapse (as described above). Careful consideration of ice-jam events within flood frequency analysis is required, particularly where there is clear evidence that it has artificially elevated water level (e.g. River Tay, 1814, described in Macdonald *et al.* (2006)). The lack of an ice-floe event within the records at Nottingham since 1814 suggests that ice-floes and jams are of limited concern within the flood frequency analysis undertaken in this paper. Long-term (end of twenty-first century) climatic change scenarios though predict increased warming and increased intense precipitation events across Central England (Hulme & Jenkins 1998). This change could result in a reduction in snowmelt influenced/dominated floods in the future, as a lack of prolonged freezing, temperatures may inhibit snowpack development.

DISCUSSION

The annual probability estimates for the Trent at Nottingham differ considerably between methods and analysed periods. The estimate from the Bayliss and Reed augmented method for the 100 year return frequency (0.01 annual probability exceedence), 1,386 $m^3 s^{-1}$, would be ranked second within both long and shorter timeframes, and appears credible in relation to past flows (Table 3). The gauged estimate of 1,161 $m^3 s^{-1}$ represents a flow comparable with the 1852 event (the third largest in the chronology since 1795 (see Table 3)). The estimates derived from the pooled and GPD approach raise serious concerns, the respective estimates for an event with an annual exceedence probability of 0.01 are 814 and 1,643 $m^3 s^{-1}$. The pooled estimate is unrealistic considering this level has been exceeded 14 times within the period since 1795, and four times during the gauged record (1958–2008). A probable cause for the poor comparison of the pooling approach, as previously detailed, is the treatment within the pooling process as a moderately urbanised catchment, coupled with the challenge in selecting a pooling group of comparable sites, as few other sites within the UK are of similar size. The estimated discharge of the 0.01 annual exceedence probability events, using the GPD is 1,643 $m^3 s^{-1}$, a discharge not observed during the history of flooding at Nottingham, raising serious concerns and reinforcing the importance of using a multiple technique approach in high magnitude flood estimation. The relative similarities between the discharge estimates from the single site and augmented approaches appear credible, suggesting that they should be used in preference to those derived from the GPD or pooled approaches (see Table 4).

The flood frequency estimates when applying the GPD approach (Figure 5(b)–(d)) for the largest flood events appear too low, thereby overestimating the frequency of the largest events and as a result raising considerable concern as to the plausibility of this approach. The estimates derived using the GPD approach in Figure 5(a), including all data, but failing the required assumptions presents apparently credible estimates, though still potentially low.

The Bayliss and Reed augmented curve and the gauged record at Nottingham provides credible estimates, which appear more reliable than the GPD and pooled estimates, when considered within the context of Table 4. The use of single site records for the calculation of low probability events should not be undertaken without the use of other methods, due to the potential that the small record lengths relative to the return frequencies of interest may fail to contain a representative number of high magnitude events as identified within the FEH (IH 1999).

The reliability of records prior to 1795 is difficult to determine; the recording of events such as those of AD 1329, 1684 and 1770 suggest that the most significant historical floods have been recorded, though smaller events may have been missed. Confidence in the documented flood accounts/descriptions is strongest for events after 1795. Multiple sources provide information concerning the 1795 event from a descriptive perspective though, as identified earlier, the earliest recorded height for the event appears to be that of Marriot & Gaster (1886). Therefore, the assumption has been made that the heights recorded after 1795 are correct, though each has been assessed independently to ensure the greatest possible reliability and accuracy.

The majority of the gauged data has been collected from what is commonly deemed a relatively ‘flood poor’ period within the UK (1950–1990), which may lead to over-estimation in flood frequency. The gauged period (1958–present) represents a longer than average gauging station record (around 30 years, Marsh & Hannaford 2008), but still represents an insufficient record length for the estimation of low probability events (2T (twice the gauged record length) is the single site requirement identified by the FEH (IH 1999).

CONCLUSIONS

The methods used in assessing the enlarged database provided by the AM series and augmented with historical records raises concerns due to the significant variations in the estimates of flood frequency at Nottingham based on the methods applied. Although there are variations between the timescales assessed (Figures 4(a), 1795–2000; 4(b), 1320–2000), the variations are not as large as they are between the methods used.

For enhanced reliability, the Bayliss and Reed augmented approach, as shown in Figure 4(a) (1795–2000) should be preferentially applied, as this includes all known events since and including that of 1795. Estimates derived from the augmented curve for the River Trent provide increased confidence to estimates derived from the single site analysis. The estimates derived from the single site (gauged) and historically augmented approaches appear realistic and are credible up to the 100-year return period. Within this study the augmented approach has been shown to be preferable to the GPD and pooled methods, as considerable concern is raised by the implausibility of the derived estimates from these approaches at low probabilities.

The principal finding from the analysis is that a multi-method approach enhances confidence in the techniques used and hence in the reliability of derived estimates, while permitting the practitioner the opportunity for adopting the most appropriate method depending on the return frequency required.

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