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Reassessing flood frequency For the Sussex Ouse, Lewes: the Inclusion of historical Flood Information since AD 1650

N. Macdonald[1], **T. R. Kjeldsen**[2], **I. Prosdocimi**[3], **and H. Sangster**[1,4]

[1]Department of Geography & Planning, School of Environmental Sciences and Institute of Risk and Uncertainty, The University of Liverpool, Liverpool, UK
[2]Department of Architecture and Civil Engineering, University of Bath, Bath, UK
[3]Centre for Ecology & Hydrology, Wallingford, UK
[4]Department of Geography, Edge Hill University, Ormskirk, UK

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Correspondence to: N. Macdonald (neil.macdonald@liv.ac.uk)

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Abstract

The application of historical flood information as a tool for augmenting instrumental flood data is increasingly recognised as a valuable tool; most previous studies have focused on large catchments with historic settlements, this paper applies the approach to the smaller lowland system of the Sussex Ouse in Southeast England. The reassessment of flood risk on the Sussex Ouse is pertinent in light of severe flooding in October 2000 and heightened concerns of a perceived increase in flooding nationally. Systematic flood level readings from 1960 and accounts detailing past flood events within the catchment are compiled back to c.1750. This extended flood record provides an opportunity to reassess estimates of flood frequency over a timescale not normally possible within flood frequency analysis. This paper re-evaluates flood frequency at Lewes on the Sussex Ouse downstream of the confluence of the Sussex Ouse and River Uck. The paper considers the strengths and weaknesses in estimates resulting from contrasting methods of analysis and their corresponding data: (i) single site analysis of gauged annual maxima; (ii) combined analysis of systematic annual maxima augmented with historical peaks of estimated magnitude; (iii) combined analysis of systematic annual maxima augmented with historical peaks of estimated magnitude exceeding a known threshold, and (iv) sensitivity analysis including only the very largest historical flood events. Use of the historical information was found to yield much tighter confidence intervals of risk estimates, with uncertainty reduced by up to 40 % for the 100 yr return frequency event when historical information was added to the gauged data.

1 Introduction

The application of historical records in flood frequency analysis has expanded rapidly over the last couple of decades (Brazdil et al., 1999, 2012; Barriendos et al., 2003; England et al., 2003; Glaser and Stangl, 2003; Macdonald et al., 2006; McEwen and

Werritty, 2007; Glaser et al., 2010) following several severely damaging floods since the early 1990s in the UK (Hannaford and Marsh, 2008) and mainland Europe (Kundzewicz et al., 1999; Szlávik 2003; Ulbrich et al., 2003; Böhm and Wetzel, 2006; Bezzola and Hegg, 2007). These extreme events have led to heightened demands for flood risk assessments that can incorporate a greater understanding of past extreme events and the methods and data used for producing them; with historical records providing an accessible and detailed account of pre-instrumental flood events (Macdonald 2012). The value of historical records is recognised in several countries with recommendations for its use in flood risk assessment in Germany, Spain, UK and USA among others, and it has become enshrined within European law (EU floods directive – 2007/60/EC). However, the application of historical information within flood frequency analysis is not a modern phenomena, as both Flood Studies Report (FSR) (NERC, 1975) and Potter (1978) encourage consideration of historical information in flood assessment, with the USGS long using historical events as a guide for the potential magnitude of extreme events (O'Connor and Costa, 2004; Stedinger and Cohn, 1986; Gaume et al., 2010). Studies incorporating historical information have often focussed on large single channel lowland floodplain dominated sites (e.g. Herget and Meurs, 2010), with long historical records arising from monastic, trade and/or political activities focused on urban centres (Macdonald et al., 2006). This study examines the flooding history of the Sussex Ouse and, in particular the area in and around the town of Lewes located in southern England (Fig. 1). In this area, the event of October 2000 flooded over 10 000 properties and caused an estimated 130 m in damages (Environment Agency, 2004); with a subsequent improvement in flood defences and development of a multi-agency flood plan (Lewes District Council, 2010).

This paper reports the findings of a study exploring the benefits of incorporating historical information into flood frequency analysis at Lewes, and the associated implications on uncertainty. More specifically, the objectives of this paper are:

1. to demonstrate the viability of incorporating historical information into flood frequency analysis

2. to consider the different approaches available and sensitivity to data availability on the Sussex Ouse, and

3. to examine the potential change in confidence (uncertainty) of derived flood estimates when incorporating historical records for extreme flood events (> 100 yr return frequency), when compared to more conventional flood frequency analysis approaches.

2 The Sussex Ouse catchment

The Sussex Ouse flows south through the North Downs, Low Weald and South Downs out into the English Channel at New Haven, past the principal settlements Haywards Heath, Uckfield and Lewes. The predominantly rural catchment consists almost entirely of ground beneath 150 m AOD, with forestry in the upper catchment and occasional settlements as previously identified (Fig. 1; Gallois, 1965). There are only few notable impoundment structures within the system, the exceptions being Ardingly Reservoir in the headwaters of the Ouse, located between the forest of St Leonards and the Ashdown and Barcombe reservoir in the lowland floodplain (c. 5 km upstream of Lewes). Mean High Water is 3.5 km downstream of Lewes, with the tidal limit at Barcombe Mills (c. 6.5 km upstream of Lewes), above the confluence of the Sussex Ouse and River Uck. The lower Sussex Ouse valley consists of thick alluvium overlying chalk with several prominent oxbows within the meandering river section, with an underlying mixed geology, with permeable outcrops particularly the Tumbridge Wells Sands and Hastings Beds in the upper Uck (Marsh and Hannaford, 2008). The distribution of precipitation across the Sussex Ouse catchment is determined largely by elevation, with northern sections of the catchment along the South Downs receiving a little over 1000 mm a^{-1}, compared to the coastal region which receives around 730 mm a^{-1} (729 mm a^{-1} at Bexhill meteorological station, just to the east of the Sussex Ouse catchment on the coast – Mayes, 1997, p. 73–74). In addition to the flood risk from the Sussex Ouse, the town of

Lewes is also at risk of flooding from the Winterbourne Stream which emerges from the chalk aquifer during periods of high water level and as such can flood in combination with, or independently of, the Sussex Ouse.

2.1 Channel management

Eastwards longshore drift has continuously replenished the shingle spit at the mouth of the Ouse resulting in intermittent phases where the Sussex Ouse has been relatively (un)impeded, resulting in inundation or draining of the Lewes Levels (Woodcock, 2003). In 1422 a Commission of Sewers was appointed to restore the banks and drainage between Fletching and the coast in an attempt to reduce flooding, but by the 1530s the Lewes Levels, some 6000 acres (24 km^2), had again returned to marshland (Brandon and Short, 1990). To counter this in 1537 a water-rate was levied on all lands on the Levels to fund the cutting of a channel through the shingle bar at the mouth of the Ouse to allow the river to drain the Levels, permitting the development of the sheltered harbour at Newhaven, succeeding the historic port of Seaford. The new channel temporarily drained the levels, but by the mid-seventeenth century the Ouse was reported as unable to drain the levels and as being unfit for navigation, by the eighteenth century the valley was again regularly inundated throughout the summer months (Woodcock, 2003). In 1790 the Ouse Navigation Act was proposed, which would straighten (canalise) the Sussex Ouse at various points, new drainage structures would be created and a western breakwater added to reduce longshore drift and prevent sediment supply to the shingle spit. The eventual results of the canalisation was 35 km of canalisation channel, 19 locks and a 1.3 km branch added, with navigation up to Balcombe. However, the improved navigation failed to be a successful enterprise, with all trade above Lewes ceasing by 1868, and navigation to Lewes only lasting until the 1950s. The consequence on the hydraulic capacity of the channel during high flow events is poorly detailed, though historical accounts (Table 1) continue to document overbank flooding during events comparable to that described by Pearce (2002) of extensive flood plain storage upstream of Lewes during flooding in 2000.

2.2 Bridges of Lewes

In central Lewes three bridges cross the Sussex Ouse: Willey's Bridge (a footbridge opened in 1965), the Phoenix Causeway (a larger road bridge built in the early 1970s), and Cliffe Bridge, which is much older and represents the sites of several historical bridges in Lewes (commonly known as Ouse Bridge; Fig. 2); in addition the modern A27 trunk road crosses the Sussex Ouse to the south of Lewes together with the adjacent railway bridge. The site of the modern day Cliffe Bridge probably reflects the location of a ford, ferry or roman bridge (Dunvan, 1795; Salzman, 1940). Accounts detailing the repair of a bridge at the site exist from as far back as 1159, with the bridge being rebuilt in 1561 and subsequently repaired in 1652, coinciding with accounts of extensive flooding (Dunvan, 1795). Historical accounts detail the bridges destruction in 1726 (Sawyer, 1890), with the current bridge dating from 1727 consisting of a single stone arch structure, it was subsequently widened in 1932 (Salzman, 1940). The adjacent wharf was constructed in 1770–71 and subsequently repaired in 1802 (Salzman, 1940), suggesting little change in the channel cross-section at Lewes during the intervening period; the first Ordnance Survey map (1875) of Lewes shows little change in channel location and adjacent structures to the present day.

3 Data sources, calibration and harmonisation

Prior to the incorporation of historical data within flood frequency analysis, an assessment of the quality and reliability of the data must be made. Where possible, individual records should be checked by cross referencing to coeval sources; when dealing with old accounts this is often challenging, but is valuable in identifying potentially spurious events (Macdonald and Black, 2010). Where peak water levels or heights have been recorded these should be critically assessed, preferably with conversion to a discharge where possible. Undertaking historical assessments can be time-consuming, and this is often cited along with lack of technical expertise as the main limitation to the inclusion of historical information in flood frequency analysis (Williams and Archer, 2002). Fortunately the development of electronic databases such as the British Hydrological Society's Chronology of British Hydrological Events (CBHE) (Black and Law, 2004) and the French, Le répertoire des repères de crues (2013) permit searching to be undertaken quickly and efficiently. For the purposes of this study, the CBHE was used as an initial resource with subsequent research undertaken examining numerous independent source materials, including documentary records (e.g. British Rainfall), local histories and newspapers; a full discussion of the different historical sources available for such studies can be found in McEwen (1987) and Brazdil et al. (2012). Inevitably the potential for modification to the channel cross section during the historical period represents a challenge when estimating historical flows, and consequently this study considers only the largest historical floods for the period since 1772. Although there are intermittent records available prior to this date, less confidence can be placed in the cross sectional area of the channel at Lewes and flood generating mechanisms being comparable to that of the present day; greater confidence can also be placed in the completeness of the records after c.1750–1800, a timeframe comparable to that selected in previous studies (Parent and Bernier, 2003; Macdonald, 2013). In this study estimates are derived using a single stage–discharge relationship, as previous work (Macdonald and Black, 2010) has suggested that during the largest flows, relatively minor modifications within the channel and catchment may have minimal impact on flood discharge. Table 1 shows the largest flood events identified from the historical records for the Sussex Ouse at Lewes. Records from AD 1750 are included, but early records are not considered as they introduce uncertainty as many appear to be derived from a single descriptive source, with these accounts syndicated to other outlets or are simply duplicated. Harmonisation of data from the various sources is required prior to the augmentation of the historical data and the gauged series. At Lewes two types of record are present:

1. Discharges from Isfield and Gold Bridge gauging station in $m^3 s^{-1}$ (1960–present).

2. Historical accounts of flooding from documentary sources which provide detailed descriptive accounts of past flood extent and therefore level.

In the following sections a combined record will be created consisting of annual maximum (AMAX) flood peaks from the recorded discharge series and the historical accounts.

3.1 Gauged flood data on the Sussex Ouse

The series used within this study is a combination of two series, as no gauged series is available for the town of Lewes itself. The tidal limit on the Sussex Ouse is above the town of Lewes, as such there is potential for tidal influence during low flows, but the potential implications for flood events are limited. The combined series uses data from two stations, Gold Bridge on the Ouse (41005; 180.9 km^2) and Isfield on the River Uck (41006; 87.8 km^2), a tributary flowing into the Ouse between Lewes and Gold Bridge; with few flows entering the system between the town and Ouse Bridge (Longford Stream and Bevern Stream have maximum discharges of 4 $\text{m}^3\,\text{s}^{-1}$ (estimated) and 5.36 $\text{m}^3\,\text{s}^{-1}$ respectively). The Maximum Daily Flow (MDF) data from the two sites were extracted from the UK Hiflows database (Environment Agency, 2013), with gaps filled with data held by the National River Flow Archives (NRFA,CEH Wallingford). This provided complete series for Gold Bridge from 1960 and from Isfield from 1964, the combined series is shown in Fig. 3, alongside the historical data dating back to 1772. An estimated discharge for the large flood on the River Uck in 1960 is available (c.100–120 $\text{m}^3\,\text{s}^{-1}$) which can be combined with the discharge from Gold Bridge to generate an estimated flow at Lewes of 165 $\text{m}^3\,\text{s}^{-1}$. The largest flows $> 150\ \text{m}^3\,\text{s}^{-1}$ appear on first inspections to have a similar frequency, though a much greater number of flows between 80–125 $\text{m}^3\,\text{s}^{-1}$ are recorded within the instrumental period.

3.2 Historical floods of the Sussex Ouse

Past flood events along the Sussex Ouse are well-documented in historical records, with some of the earliest accounts detailing flooding from a combination of fluvial and coastal sources: “By the early fourteenth century, highly- prized meadow had been inned and embanked but its value was increasingly reduced by the recurrent inundations during the later middle ages resulting from the fall in the relative level of land to sea and the increased storm-tide frequency. Despite the raising of the banks, winter flooding was common in the fourteenth century and frequently the flood waters remained throughout the summer on the lower meadows and occasionally submerged crops on the bordering flanks” (Glynde MS 996). Many of the earliest accounts are concerned primarily with droughts, particularly those of the mid-fourteenth century. This is unusual for most British catchments, where floods dominate the early records. The earliest account to detail flooding in Lewes specifically comes from the AD 1772 flood, in which “The floods of January 1772 saw boats floating round the Bear Inn adjoining the bridge. . . ” (Rector, 1961, p.240). The descriptions provided by accounts often reflect on similar aspects, during the 1852 flood in Lewes a local newspaper, the Morning Chronicle, in part of its description details “Boats were rowing and sailing about” (Anon, 1852). The common reference to floating boats affords a degree of comparison between this event and the earlier event of 1772 to be made. Historical accounts can also provide useful information on the effects of floods; these can help shape understanding of past responses and cultural practices in the face of such events (McEwen et al., 2013). For example, Rector (1961, p. 240) reports that “In December 1801 the floodwaters nearly caused a disastrous fire in Swing-pump Alley (now North Court) when they entered a building containing a quantity of slaked lime. The blaze was formidable, but was soon brought under control. . . ”. Unlike at other sites where historical accounts detail flood events back to the thirteenth century (e.g. Macdonald, 2013), no such accounts exist at Lewes from which estimates of flood magnitude can be made, the earliest stems from 1772, which falls within the period from which reasonable confidence exits that all subsequent events exceeding a high threshold are known.

3.2.1 Winterbourne stream

A number of floods affecting Lewes have originated from the Winterbourne Stream, which drains a small catchment (18 km^2) to the west of Lewes. It is an ephemeral stream draining the Chalk Downs, for much of its course it is culverted, emerging just downstream of Cliffe Bridge where it joins the Ouse, though historical accounts document that the lowland section was previously marsh, which flooded regularly in the Spring. The catchment is now highly urbanised with several subsurface impoundment features included within the modern flood management structures. Historically floods are recorded prior to 1900 in 1772, 1801, 1814, 1829, 1852, 1875 and 1894 (Defra, 2008), with affected properties in several streets within the town but did not cause widespread flooding. Flood accounts within the historical records may reflect flooding from the Winterbourne rather than directly from the Ouse, as such care should be taken in the interpretation of the historical accounts to consider this.

4 Flood frequency analysis

The inclusion of historical records inevitably involves the assumption that the AMAX values in the historical series would not be known unless they cross a certain perception threshold. It is also assumed that all events crossing the perception threshold will be known (Stedinger and Cohn, 1986). The selection of the threshold can be evaluated by considering the frequency of events above the threshold. The frequency of events recorded in the historical and gauged periods should ideally be comparable. More sophisticated techniques are available for assessing these assumptions (e.g. Renard et al., 2006). In the subsequent analysis two thresholds were considered: initially a threshold of 100 m^3 s^{-1} was proposed that provided exceedance rates that were quite different, between the historical and instrumental periods; consequently, a threshold of $150\,\mathrm{m^3\,s^{-1}}$ was defined which produces sufficiently comparable exceedance rates between the two periods. For the purpose of this study, the second threshold will be used in subsequent analysis, though the issue of thresholds will be further developed in the discussion.

In the UK flood frequency analysis typically involve fitting a Generalised Logistic (GLO) distribution to annual maximum (AMAX) series of peak flow events using the method of L-moments as described in the Flood Estimation Handbook (IH, 1999); see Castellarin et al. (2012) for a more wide-ranging review of European statistical procedures applied in flood frequency analysis. However, no conclusive method has been developed within the L-moment framework for easily combining systematically gauged data with censored historical events in the historical period pre-dating the installation of a gauging station. Consequently, this study has adopted the probabilistic model for a censored AMAX series formulated as maximum-likelihood function as proposed by the Flood Studies Report (FSR) published by NERC (1975) and Stedinger and Cohn (1986). The model assumes that the AMAX events from both the gauged and the historical period are independent and follow the same distribution, which in this case is proposed to be the GLO distribution with a probability density function (pdf) and a cumulative density function (cdf) defined as:

$$f_x(x) = \frac{\alpha^{-1} e^{(1-\kappa)y}}{(1+e^{-y})^2}, \quad y = \begin{cases} -\kappa^{-1}\ln(1-\kappa(x-\xi)/\alpha) \\ (x-\xi)/\alpha \end{cases} \tag{1}$$

$$F_x(x) = \frac{1}{(1+e^{-y})} \tag{2}$$

where ξ, α, and κ are the location, scale and shape parameters, respectively. The record of AMAX events from the gauged record consists of n events $(x_1, x_2 \ldots x_n)$, which are considered to be monitored with confidence across the entire flow regime, i.e. no censoring of these events is evident and no systematic/measurement error is present in the records. Next, historical events are only recorded if they are of a relevant magnitude, which is to say if they exceed the perception threshold value, X_0. A total of k historical events $(y_1, y_2, \ldots y_k)$ cross the perception threshold over a total period of h years, defined as stretching from the start of the historical record until the beginning of the systematic record. This leaves a total of $(h-k)$ years in the historical records for which the only information available on the AMAX event is that it did not exceed the perception threshold. For each year in the historical record the annual maximum exceeds the threshold with a probability $p = [1-F_x(X_0)]$ and the number, k, of threshold exceedances can be modelled as a binomial random variable $K \sim \mathrm{Bin}(h,p)$. In order to take into account not only the information that a large event occurred in the past, but also the calculated size of the historical events, the probability density function of the historical events is calculated. Since the size of a historical event is only known if it exceeded the perception threshold, the historical events above the threshold follow a conditional distribution $f_x(y|y > X_0)$. Considering that

$$\begin{aligned} f_x(y) &= f_x(y|y > X_0)[1-F_x(X_0)] + f_x(y|y < X_0)F_x(X_0) \\ &= f_x(y|y > X_0)[1-F_x(X_0)] \end{aligned} \tag{3}$$

and since $f_x(y|y < X_0) = 0$, the conditional distribution of the historical event can be rewritten as

$$f_x(y|y > X_0) = \frac{f_x(y)}{1-F_x(X_0)}. \tag{4}$$

Having defined the distribution for both gauged and historical data above, the full likelihood function describing the data series can now be defined as

$$f(x) = \underbrace{\prod_{i=1}^{n} f_x(x)}_{\text{a}} \underbrace{\left\{ \begin{bmatrix} h \\ k \end{bmatrix} F_x(X_0)^{h-k}[1-F_x(X_0)]^k \right\}}_{\text{b}} \underbrace{\prod_{j=1}^{k} f_x(y_j|y_j > X_0)}_{\text{c}} \tag{5}$$

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where the three terms a–c represent contribution to the total likelihood function from the different data types: (a) gauged AMAX events, (b) the h years in which the threshold X_0 was exceeded k times, and (c) the distribution of the recorded historical events. By substituting Eq. (4) into Eq. (5), the likelihood function is simplified to include only the unconditional distribution, i.e.

$$L = \prod_{i=1}^{n} f_x(x_i) \begin{bmatrix} h \\ k \end{bmatrix} F_x(X_0)^{h-k} \prod_{j=1}^{k} f_x(y_i) \tag{6}$$

In the case where it is only known that an event exceeded the perception threshold, but the actual magnitude is not know, the last term of the likelihood function in Eq. (6) is changed to reflect this level of knowledge, i.e.

$$L = \prod_{i=1}^{n} f_x(x_i) \begin{bmatrix} h \\ k \end{bmatrix} F_x(X_0)^{h-k} \prod_{j=1}^{k} [1 - F_x(X_0)] \tag{7}$$

For both situations the three GLO parameters are estimated by maximising the value of the log- likelihood function in Eqs. (6) and (7) using numerical optimization. The output from the maximum-likelihood parameter fitting is a vector of the estimated parameter values $\hat{\mathbf{v}} = \left(\hat{\xi}, \hat{\alpha}, \hat{\kappa}\right)$ and the associated covariance matrix $\mathbf{\Omega}$ where the elements represent the variance-covariance of the three estimated GLO parameters. The flood frequency curve is defined as the quantile function of the GLO distribution, which is itself the inverse of the cdf in Eq. (2), and from which the design flood event with a return period T can be estimated as

$$\hat{x_T} = \hat{\xi} + \frac{\hat{\alpha}}{\hat{\kappa}}(1 - \left(T - 1)^{-\hat{\kappa}}\right) \tag{8}$$

The total uncertainty of the estimated T year flood will be made up by contributions from: (1) sampling uncertainty from estimating model parameters from a limited number of data, (2) model uncertainty because the GLO distribution might not be the true underlying distribution, and (3) uncertainty embedded in the reported values of the AMAX events; both gauged and historical data. In this study we will only consider the sampling uncertainty, but acknowledge that especially the data uncertainty and the difference between gauged and historical events could be a significant factor. Other researchers have developed more complex methods to more comprehensively capture the different uncertainty components, notably Gaume et al. (2010) and Nappel et al. (2010). However, for the purpose of this study is to investigate the utility of the historical data, the sampling uncertainty was considered adequate.

As the estimator in Eq. (8) is non-linear, the Delta method is adopted to obtain a confidence interval for the T years event. A Taylor expansion is used to obtain a linearised version from which the variance can be readily obtained as described by Kjeldsen and Jones (2006). Consider that the estimator $\hat{x}_T$ in Eq. (8) is an estimate of the true (unknown) value x_T and is a function of a vector of estimated parameters,$\hat{\mathbf{v}}$, whose true value is $\mathbf{v}$, thus $\hat{x}_T = g(\hat{\mathbf{v}})$. Then the Taylor approximation gives

$$\hat{x}_T \approx g(\mathbf{v}) + \mathbf{d}^{\mathbf{T}}(\hat{\mathbf{v}} - \mathbf{v}) \qquad (9)$$

where the elements d_i in the vector $\boldsymbol{d}$ are given as $d_i = \partial g / \partial v_i$ evaluated at $\boldsymbol{v}$. It then follows that the variance of the T year event can be expressed as

$$var\{\hat{x}_T\} \approx \mathbf{d}^{\mathrm{T}}\mathbf{\Omega}\mathbf{d}. \qquad (10)$$

Having estimated the variance, the corresponding 95 % confidence interval of the T year event is obtained approximately, assuming the T year event to be normally distributed, as plus and minus 2 times the standard deviation.

5 Results

The combined flood series for the Sussex Ouse consists of five historical floods (out of ten – Table 1) and two floods from the gauged series (1960 and 2000) which exceed the perception threshold of 150 $m^3 s^{-1}$. The historical record covers a period of 210 yr starting in 1750 and ending in 1959 with the onset of data from systematic gauges initiated in 1960. The most recent water year included in the gauged series is 2010 (last event occurring 11 January 2011). For two years, 1962 and 2005 no MDF data are available and are considered missing. The gauged record therefore consists of 49 AMAX events observed over a period of 51 yr, and thus the combined record covers a total period of 261 yr (1750–2010) and is shown in Fig. 3. In the subsequent flood frequency analysis for the Sussex Ouse at Lewes, three different methods will be assessed, reflecting three different levels of availability and confidence in the dataset:

- Single site analysis of the 49 AMAX events in the gauged record
- Flood frequency analysis of the combined record considering the peak discharge of the historical events to be exactly known
- Flood frequency analysis of the combined record considering the peak discharge of the historical events to be unknown, but known to exceed a defined perception threshold

Finally, the impact of the level of the perception threshold will be conducted to assess the sensitivity of the method.

5.1 Flood frequency analysis

For each of the three methods, the estimated parameters (location $\hat{\xi}$, scale $\hat{\alpha}$, shape $\hat{\kappa}$) of the GLO distribution are reported in Table 2 together with the estimated 100 yr design flood and the associated standard deviation. The fitted GLO models are plotted, including confidence intervals, against the observed AMAX in two different figures. Figure 4 shows the GLO distribution fitted directly to the 49 AMAX events in the gauged record. The position of the individual AMAX events in Fig. 4 is determined through use of the Gringorten plotting position. Figure 5 shows the GLO distribution fitted to the combined data series for the three cases (gauged only, known and unknown discharge of historical peak discharge). The plotting positions for the events in the combined record were calculated using the revised formula of the (Bayliss and Reed, 2001). Note that introducing the historical floods will result in a different set of plotting positions being assigned to each of the events in the gauged record when compared to the set derived using the Gringorten methods on the gauged data only, thus the two plots in Figs. 4 and 5 show different positioning of the gauged events on the flood frequency plots. From the results in Table 2 it can be observed that the introduction of historical events has reduced the magnitude of the estimated 100 yr event by 16 %, and at the same time reduced the standard error by 46 % for the case where the historical events are assumed known, and by 42 % when the peak discharge is unknown. These results illustrate that, for this case study, the inclusion of the historical evidence has resulted in a more precise estimate of the flood risk, thus highlighted the potential benefits of incorporating historical information into the flood frequency analysis.

5.2 Sensitivity analysis

A key assumption in the analysis is the definition of the perception threshold, X_0. In the flood frequency analysis documented in the previous section a fixed perception threshold value of $X_0 = 150\,\mathrm{m^3\,s^{-1}}$ was adopted, which resulted in only five out of the ten historical events being included into the analysis. To test the sensitivity of the results to the choice of threshold level, a sensitivity analysis was conducted by fitting a GLO distribution to a number of combined data series, each containing the complete gauged series, but a varying number of historical events. The ten historical events were ranked in ascending order, and the perception threshold defined to equal the discharge for each event in turn (or events where several events were found to have the same discharge). This resulted in a total of seven different combined data series based on perception threshold values of $X_0 = (100, 130, 150, 175, 190,$ and $230\,\mathrm{m^3\,s^{-1}}$, where the lowest threshold of $X_0 = 100\,\mathrm{m^3\,s^{-1}}$ contains all ten historical events, whereas the highest threshold value of $X_0 = 230\,\mathrm{m^3\,s^{-1}}$ contains only the 1772 events in the historical dataset. It is noticeable that the flood frequency curve obtained when including all ten historical events (curve 1 in Fig. 6) is visibly different from most other curves. The smallest historical flood magnitude in the series is $100\,\mathrm{m^3\,s^{-1}}$ (recorded in November 1810 and January 1916). In contrast, the number of events in the 51 yr gauged record (1960–2010) exceeding the $100\,\mathrm{m^3\,s^{-1}}$ threshold is twelve, thus a comparison of the exceedance rate between the two series gives:

- Historical series: 10 events $> 100\,\mathrm{m^3\,s^{-1}}$ in 210 yr, rate $= 0.05$ events $\mathrm{yr^{-1}}$
- Gauged series: 12 events $> 100\,\mathrm{m^3\,s^{-1}}$ in 51 yr, rate $= 0.23$ events $\mathrm{yr^{-1}}$

While exceedance rate is only one aspect of a comparison, it is immediately clear that for such a low threshold value, substantially more historical events should have been identified before it could reasonably be concluded that the two data series (historical and gauged) are both realisations of the same underlying distribution. As the perception threshold increases, the difference between the estimated flood frequency curves becomes smaller, while the loss of data results in an increase in the standard deviation of the 100 yr event. When only the one or two largest historical events are included, the resulting 100 yr design flood estimate is relatively close to the estimates obtained from the gauged series alone, $235\,\mathrm{m^3\,s^{-1}}$ (see Table 2), while the standard deviation of the combined records are still substantially (about 43 %) below the $40\,\mathrm{m^3\,s^{-1}}$ obtained from the use of the gauged series only.

6 Discussion

The inclusion of historical information in augmenting instrumental series is dependent on suitability, level of detail, reliability and availability of accounts, all of which are site specific. The selection of Lewes for this study was based on the identification of a historic settlement, but one which is based in a relatively small catchment, without a well reconstructed flood history where no epigraphic markings (Macdonald, 2007) are present and which could be considered as representative of many catchments in the UK and elsewhere. This provided a valuable case study, as unlike many previous historical flood studies it was not based on a historically significant city or on a river within a very large catchment. Threshold selection is a fundamental component within any analysis, with careful consideration required ensuring that there is compatibility between gauged and ungauged data series in the number of high magnitude events, but as clearly shown the greater number of events included can have significant implications on the estimates derived, with greater number of events reducing the associated magnitude of any specified design flood at Lewes (Fig. 6).

The inclusion of historical floods within a combined historical-instrumental flood series at Lewes reduces the uncertainty of design flood estimates of long return periods when compared to using just an instrumental flood series (Fig. 5). The differences between using exact discharges or knowing only that a historical event exceeded a perception threshold value has almost the same value, this is important as it indicates that for those events within the historical series where the discharge is unknown, but where they are known to exceed a specified threshold, inclusion provides valuable data; this supports the findings of Payrastre et al. (2011). This represents an important finding for future historical flood event inclusion and can be of significant assistance to those tasked with reconstructing historical flood series, as it identifies that specific discharges, whilst valuable, are not necessary required with threshold exceedance but are a valuable tool when estimating high-magnitude events.

The use of historical flood information assumes that the generating mechanisms responsible for high magnitude events have remained relatively stable over the last c.250 yr (as shown by Macdonald, 2012 for NE England) and that land-use is unlikely to have changed the capability of the catchment to produce and/or propagate large flood events (see Macdonald, 2012; Fouldes et al., 2013), or that the hydraulic properties of the channel have changed significantly during the intervening period (Herget and Meurs, 2010; Elleder et al., 2013). The evidence from Lewes suggests that these assumptions are fair to maintain, as the historical accounts and the maps, construction of the main channel features principally took place before or near the start of this period. The use of the historical records also reduces the likelihood of broader short-term phases which may be either flood poor (1970–1990) or flood rich (2000-present) disproportionally affecting the return frequency estimates (see Macdonald and Black, 2010).

7 Conclusions

The principal finding of this research are that the inclusion of the largest historical events can have important implications on flood frequency estimation (Table 2), the approaches applied provide greater confidence in the derived estimates with the historical records reducing the uncertainty for high magnitude flood event estimation (> 100 yr return frequency), in this study by around 40 %. The use of historical information in a combination of approaches, for comparison and corroboration, together permit a more confident flood risk assessment at Lewes than would otherwise be possible. The sensitivity of the application of threshold is important with clear evidence that the selection of threshold, if set to low, can have a detrimental effect on the confidence of the derived flood frequency results as comparability between the series is undermined, but also if set to high has a lower impact on the estimates but can still lead to decreased uncertainty. Therefore, threshold selection remains a function of user expertise, though simply knowing a flood event exceeded a threshold can have almost the same value in flood estimation as a specific estimate or series of estimates. The findings of this paper support the call at both national (e.g. MARM, 2011; Miquel, 1984) and international (USWRC, 1982) levels for greater use of historical flood information in flood frequency analysis, as a means by which uncertainty can be reduced in high magnitude flood estimation.

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Table 1. Historical floods in the Sussex Ouse.

Date	Account	Source	Estimated discharge (m^3 s^{-1})
January 1772	Lewes: "… The floods of January 1772 saw boats floating round the Bear Inn adjoining the bridge…"	Rector (1961)	235
December 1801	Lewes: "… in December 1801 the floodwaters nearly caused a disastrous fire in Swing-pump Alley (now North Court) when they entered a building containing a quantity of slaked lime. The blaze was formidable, but was soon brought under control…"	Rector (1961)	175
November 1810	"When the rainfall is very great, the low districts in the county [Sussex] become flooded. The chief places thus inundated are the levels around Pulborough, Arundel, Bramber, Beeding, Henfield, Lewes and Pevensey. In November 1810, these places were flooded, and at Arundel the water was seven feet deep in the levels…"	Symons (1872, 164)	100
December 1839	"When the rainfall is very great, the low districts in the county become flooded. The chief places thus inundated are the levels around Pulborough, Arundel, Bramber, Beeding, Henfield, Lewes and Pevensey… in December 1839, severe floods."	Symons (1872, 164)	130
Autumn, 1841	"When the rainfall is very great, the low districts in the county become flooded. The chief places thus inundated are the levels around Pulborough, Arundel, Bramber, Beeding, Henfield, Lewes and Pevensey… from October to December 1841, and in February 1847, floods were caused by the melting of snow."	Symons (1872, 164)	130
31 Oct, 1852	"The heavy and long-continued rains have produced disastrous floods in all parts of the country. The local journals are filled with accounts of inundations, which have destroyed the fruits of rural industry to a vast amount and occasioned incalculable damage. At Lewes, the torrents which poured down from the hills covered the face of the low ground for miles - boats were seen traversing the meadows; the traffic on the railway was suspended, and the water burst into the cellars and overflooded the streets in the lower part of the town. Stacks of corn and hay, planks, and rural produce were carried away, and many sheep drowned."	Annual Register (1853)	230
	Uckfield town: "Major flood events occurred in 1852,… the information collated was considered sufficiently robust to provide the following ranking for each of the major floods during the last 150 yr: Rank 2–23 October 1852 …)"	Macdonald (2004)	
26 Oct, 1865	Uckfield town: "Major flood events occurred in… 1865,… .the information collated was considered sufficiently robust to provide the following ranking for each of the major floods during the last 150 yr: Rank 5–26 October 1865…)"	Macdonald (2004)	150
	Rainfall observer at Uckfield, Sussex [river Uck, tributary of the Sussex Ouse] was noted as reporting "Highest flood since 1852"	Symons (1875, 71)	190
11 Nov, 1875	Uckfield town: "Major flood events occurred in … 1875, … the information collated was considered sufficiently robust to provide the following ranking for each of the major floods during the last 150 yr: Rank 3–11 November 1875 …)"	Macdonald (2004)	190
January 1916	Uckfield town: "Major flood events occurred in … 1916 …"	Macdonald (2004)	100
January 1925	Lewes: "… Again severe flooding occurred in January 1925, business premises in Cliffe High Street being badly damaged."	Rector (1961)	130
November 1960	Lewes: "Floods are an old story to Lewes. All through the years the lowlands around the town have been prone to flooding and the people of Cliffe have suffered in particular. It is unusual however that, as in the case of the 1960 floods, the Winterbourne Stream should become such a menace … The first week in November 1960 saw the worst floods that Lewes experienced since 1925."	Rector (1961)	

Table 2. Estimated GLO parameters, 100 yr design flood and the associated standard deviation.

Method	GLO parameters ξ	α	κ	x_{100} $m^3 s^{-1}$	$sd(x_{100})$ $m^3 s^{-1}$
Single site	69.5	17.7	−0.28	234.8	39.9
Historical data of know magnitude	68.0	15.9	−0.23	197.3	21.6
Historical data of unknown magnitude	68.1	15.9	−0.23	196.3	23.2

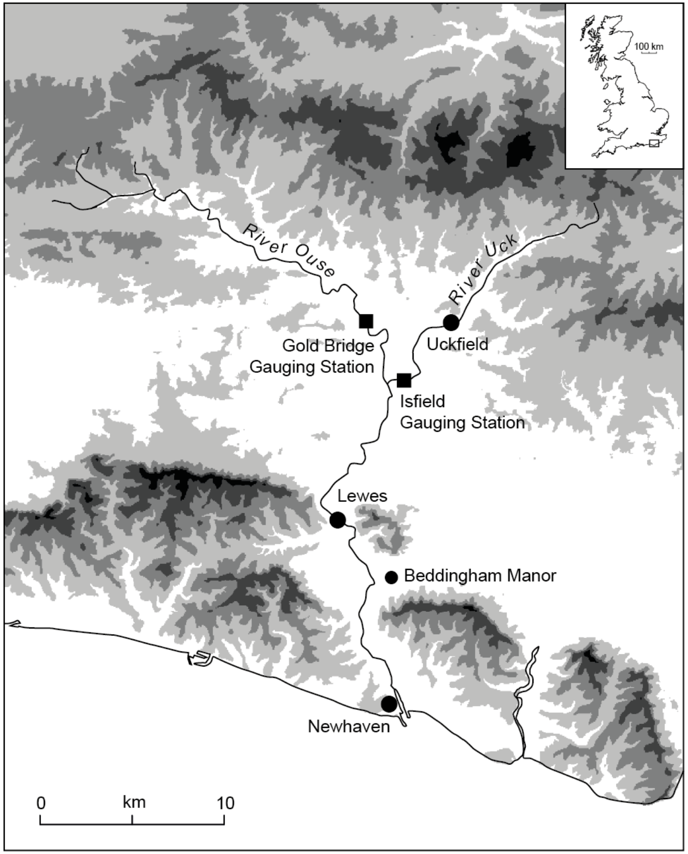

Fig. 1. The Sussex Ouse catchment.

Fig. 2. Ouse Bridge, central Lewes looking downstream (Amy Lennard).

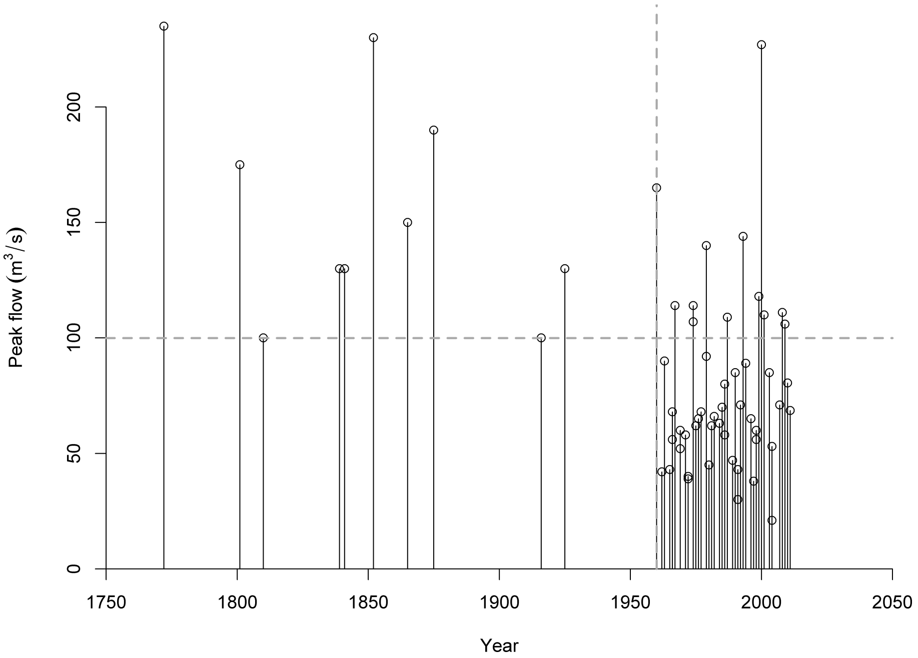

Fig. 3. Combined historical and gauged series of AMAX events for the Sussex Ouse.

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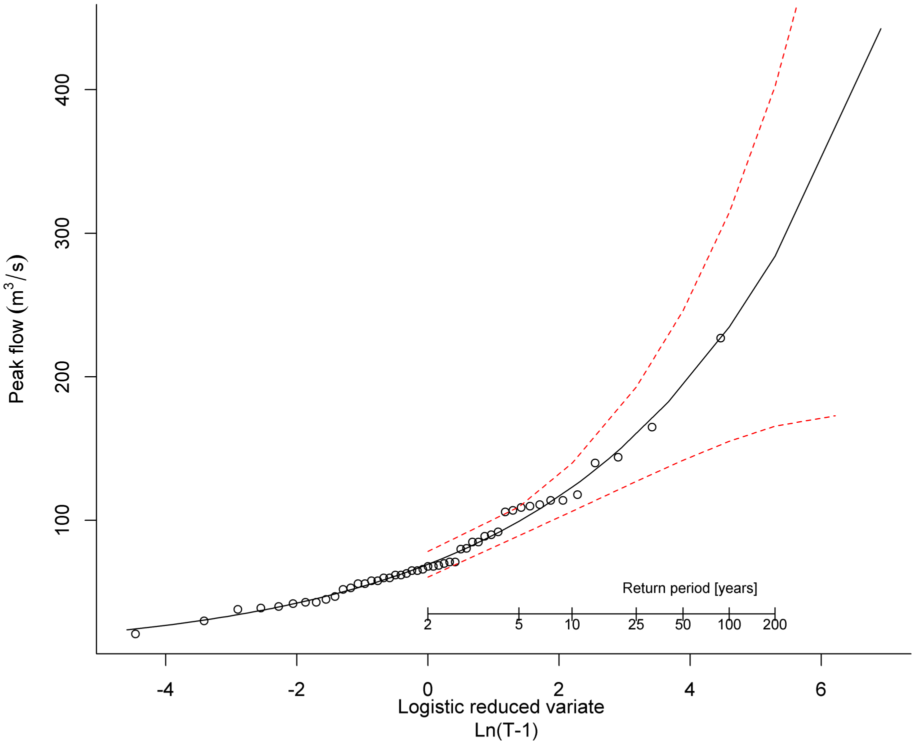

Fig. 4. GLO distribution fitted to the 49 AMAX events from the gauged record (1960–2010).

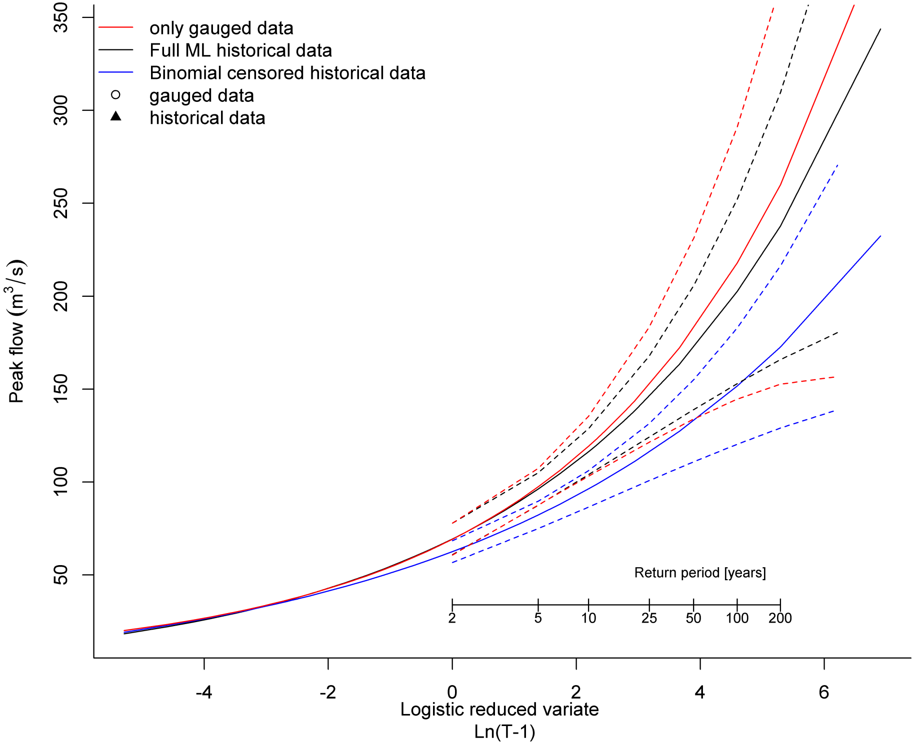

Fig. 5. GLO distributions fitted to gauged data only, and the combined data series with historical events considered the peak discharge value to be known (full) and unknown (binomially censored). Hatched lines show the upper and lower 95 % confidence intervals for the three different flood frequency curves.

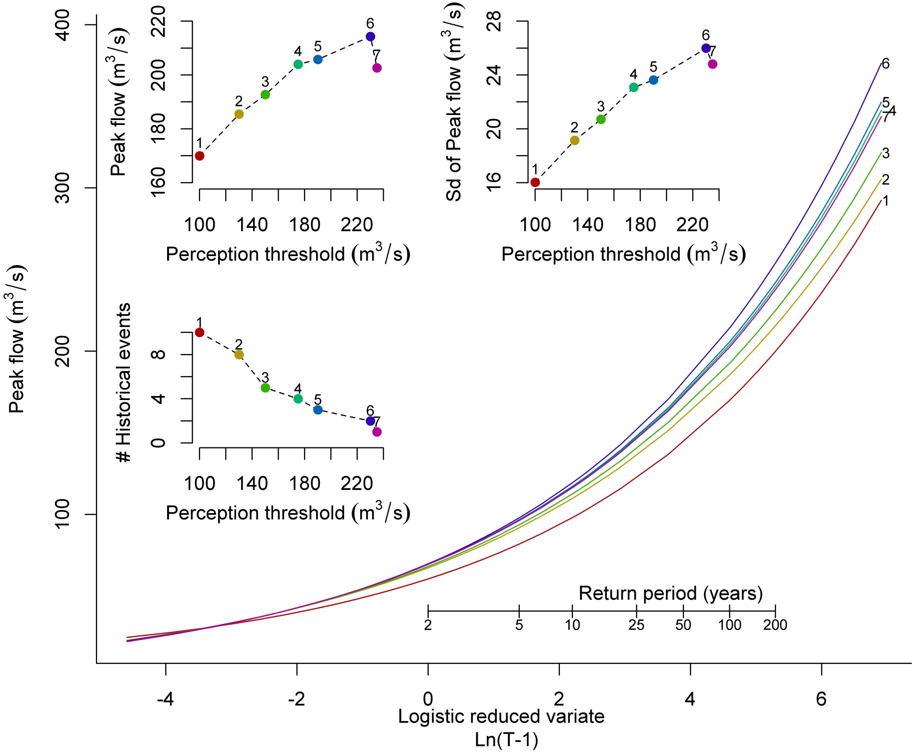

Fig. 6. Sensitivity analysis of flood frequency curves fitted to the 49 gauged AMAX events combined with seven different threshold levels. The insert figures show the sensitivity of: **(a)** the estimated 100 yr design flood; **(b)** the standard deviation (sd) of the 100 yr design flood; and, **(c)** the number of historical events used in the fitting. The numbers 1 to 7 in all graphs refers to the seven combined data series.