

Practical application of historical flood information to flood estimation

DAVID ARCHER

Jeremy Benn Associates, The North Barn, Broughton Hall, Skipton, North Yorkshire BD23 3AE, UK

e-mail: david.archer@jeremybenn.co.uk

Abstract Recent UK legislation requires assessment of 100-year return period flood levels for flood plain planning control. Typical gauged data lengths give an unreliable estimate and the merits of regionalization and the use of historic data are discussed. Typically, existing methods of incorporating historic data require the assessment of event discharges when often all that can be assessed from available sources is the number of events in a specified period over a threshold. Whilst this may be considered statistically as a binomial censored sample, a graphical procedure based on the exceedence of the largest gauged discharge is demonstrated for two contrasting cases of the Rivers Wansbeck and Leam in England using data covering a period of over 200 years. These demonstrate both the limitations and the usefulness of incorporating historical flood data.

INTRODUCTION

The Environment Agency of England and Wales is required under recent legislation to assess flood levels and extent in a fluvial flood event of 100-year return period. Conventionally this requires first the hydrological estimation of a 100-year flood discharge followed by hydraulic modelling to convert discharge to level. Target accuracies for levels based on hydraulic modelling are ± 250 mm but the accuracy of estimation depends at least as much on the hydrological assessment of discharge as on hydraulic modelling.

As a basis for flood estimation, gauged records in England and Wales typically range from 25 to 40 years. Annual maximum flood discharges from gauged data may be used to determine flood flows of specified return period. However there is a danger that the sample may be unrepresentative of the population of floods and extrapolation of a flood frequency distribution based on such a sample may yield highly unreliable estimates of the 100-year flood discharge. For example, assuming a Poisson distribution of inter-event times there is a 22% chance of a 25-year data set containing a flood of more than 100-year return period.

The limitations of theoretical flood frequency and fitting techniques are evident when the data set contains significant outliers. The data themselves do not provide a basis for judgement as to whether the recurrence interval is equivalent to the plotting position of the outlier for the observed flood series or much higher as may be suggested by applying different distributions and fitting methods. There are two basic approaches to improve the reliability of estimates which may be used separately or in combination: flood regionalization and the incorporation of historical flood data.

FLOOD REGIONALIZATION

Flood regionalization provides a means of extending the effective data length by combining records from catchments which are geographically contiguous or which share physical flood generating characteristics. It can also be used to devise methods of estimation in ungauged catchments through the use of catchment characteristics. The Flood Studies Report (NERC, 1975) provides such methods for the British Isles through the use of an index flood (the mean annual flood Q_{BAR}) and a regional growth curve of Q_T/Q_{BAR} .

However regionalization depends upon homogeneity in flood frequency characteristics amongst the catchments included in "a region". The current Flood Studies regions have been criticized for abrupt discontinuities at region boundaries and for systematic spatial variations of residuals within a region (Archer, 1981). Alternative methods of regionalization have been proposed, for example by Acreman & Sinclair (1986), based on cluster analysis, but are not yet in use.

The UK Institute of Hydrology is currently revising methods of regionalization of flood statistics using much longer data sets than were available in the original analysis. Nevertheless, perfect homogeneity between catchments cannot be expected and catchments may show greater individuality in flood response at higher return periods, for example as the results of the effects of flood plain attenuation on flood growth (Archer, 1989), where real differences in behaviour are more difficult to distinguish from sampling variation.

Whilst regionalization, with or without historical data, clearly has a principal part to play in flood estimation, the discussion below is limited for the sake of brevity to the role of historical data in extending the record based on gauged data.

USE OF HISTORICAL DATA

Historical flood information collected before the advent of consistent scientific measurement can also potentially be used to extend the effective data length for a catchment. The observation of level by untrained observers at sites not specifically designed to convert observed levels to discharges poses additional questions concerning the reliability or value of such information. However, the fact that such data are observed on the catchment in question avoids the problems of combining records from catchments with dissimilar response. Experience of historical flood data indicates that useful information, but of varying quality, may be obtained for a period of at least 150 years in virtually every flood-prone catchment in England.

Historical flood information comes from a wide variety of sources and in different formats. These include repeated gauge observations at mills and bridges, general descriptions in newspapers and elsewhere of flood extent and levels in buildings, contemporary comparison with previous floods and associated meteorological information.

FLOOD FREQUENCY ANALYSIS INCLUDING HISTORICAL DATA

Historical data have been increasingly incorporated in flood frequency analysis. Numerous alternative methods have been described, generally combining historical

data with gauged discharges in a censored data framework (Leese, 1973; Hosking & Wallis, 1986; Stedinger & Cohn, 1986). The total data length (N_T) is the sum of the systematic and continuous gauged record (N_S) and the intermittent historical record (N_h) (Fig. 1). The total number of exceedences (k_T) above a threshold (Q_0) is the sum of those for the gauged period (k_s) and for the historical period (k_h). Censoring of flood samples is of two types. In Type I the threshold is known and fixed and the number of exceedences is a random variable. For Type II censoring, the threshold is assumed to be the random variable with k fixed in advance. The latter may be used with $k = 1$ where only the largest flood was included (Hosking & Wallis, 1986).

The value of historical information has been investigated in a number of studies. Stedinger & Cohn (1986), assuming Type I censoring, used a Monte Carlo experiment with a lognormal distribution and maximum likelihood estimates to show that an equivalent of 10–30 years of gauge record can be extracted from a 50-year period of historical observation. Hosking & Wallis (1986), on the other hand, found historical data to be much less helpful, but Guo & Cunnane (1991) indicated that their poor results were primarily due to the Type II censoring assumption.

The assumed value of N_h has been shown by Hirsch & Stedinger (1987) to be a critical factor to estimate. Typically this is specified to commence with the occurrence of the first historical flood (NERC, 1975) but Hirsch & Stedinger argue that this is a biased estimator and that a value based on historical judgement should be used.

In assessing the value of historical data the following typical assumptions are made to simplify evaluation (England *et al.*, 1998):

- both gauged and historical discharges are error-free;
- the historical period N_h is known perfectly;
- the threshold discharge Q_0 is known with accuracy.

In reality, these assumptions are always violated, but the extent to which they are limiting is concealed as the reported statistical analysis is rarely set alongside the

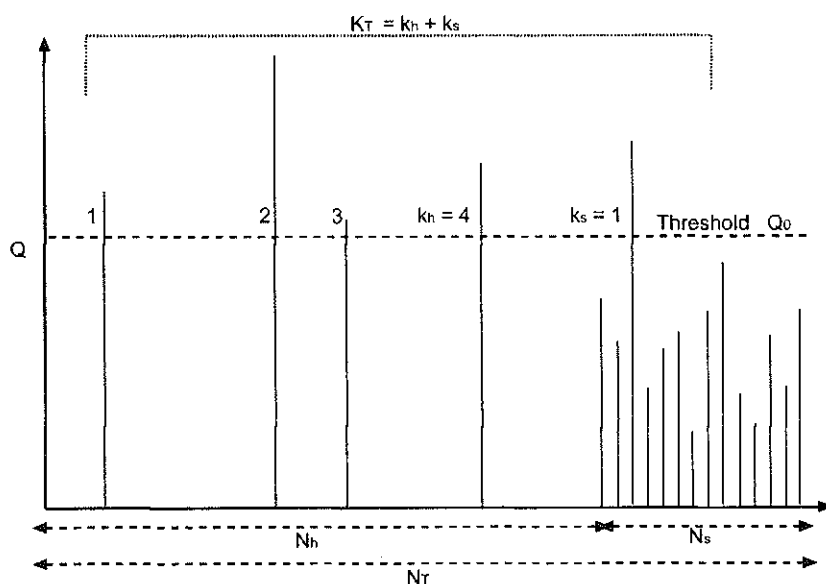


Fig. 1 Censoring framework for historic floods.

methods and sources of historical data. The estimates of gauged peak discharges may also be considerably in error.

Nevertheless it is argued that historical flood information can greatly increase the reliability of flood estimates at longer return periods above those based solely on short period gauged data and on the extrapolation of assumed distributions. This can be done even without the conversion of historical levels to discharges by consideration of the frequency with which the highest gauged flood was exceeded in the historic period, i.e. the threshold Q_0 is set equal to the largest gauged flood, effectively equivalent to Type I censoring. Historic flood identification and analysis are described for the River Leam in the English Midlands and for the River Wansbeck in northeast England.

River Wansbeck

The River Wansbeck with a total catchment area of 340 km² drains to the North Sea (Fig. 2, inset). A gauging station at Mitford (287 km²), with a 34-year record of annual maxima, lies a short distance upstream from the principal vulnerable area in the town of Morpeth, part of which is built on the flood plain in a meander loop of the river.

In the highest recorded flood event in March 1963 some 480 houses plus industrial and commercial premises were flooded. The assessed flood discharge for this event of 364 m³ s⁻¹ is 1.54 times the Rank 2 flood in the series. A series of two- and three-parameter distributions and fitting methods was used to provide preliminary estimates of flows of specified return period as follows:

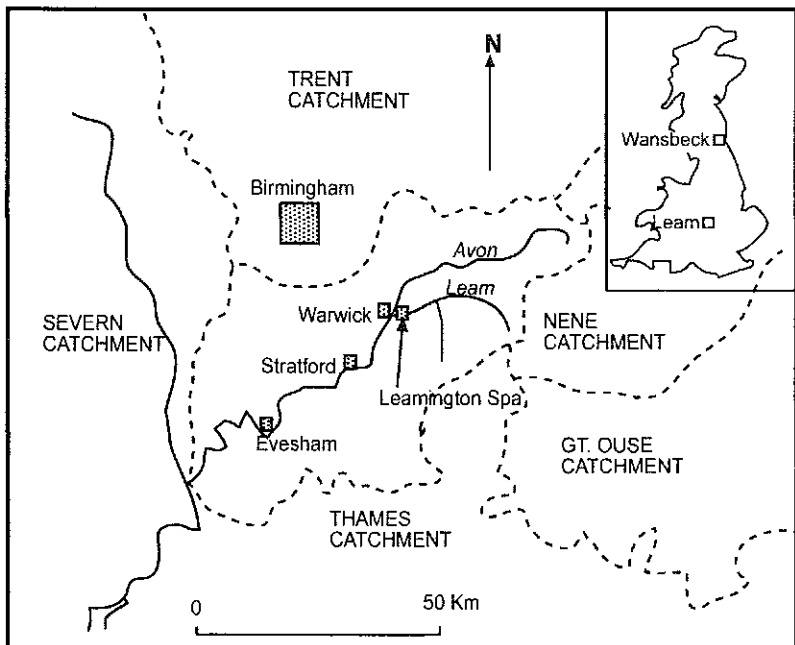


Fig. 2 The River Leam in its regional context and, inset, location of the Wansbeck and Leam catchments in the UK.

Extreme Value Type 1	Maximum likelihood (EV1-MLE)
Extreme Value Type 1	Probability weighted moments (EV1-PWM)
Extreme Value Type 1	Method of moments (EV1-Mom)
Generalized Extreme Value	Maximum likelihood (GEV-MLE)
Generalized Extreme Value	Probability weighted moments (GEV-PWM)

The methods respond quite differently to the occurrence of an outlier and the assessed return period of the 1963 discharge ranged from 54 years (GEV-MLE) to 625 years (EV1-MLE) giving a correspondingly wide range in estimate of the 100-year return period flow, from 284 to 451 $\text{m}^3 \text{s}^{-1}$ (Fig. 3).

A review of the history of flooding on the Wansbeck was carried out by Archer (1992). Descriptive information was available from newspapers from the early eighteenth century. In addition, engraved flood stones at two mill locations downstream from Morpeth show comparative levels of major floods from 1878. Over that period, the 1963 flood was still the highest, exceeding a flood in 1898 by 0.10–0.18 m and a flood in 1878 by 0.5 m.

Significant floods also occurred in 1831 and 1839, the former being “higher than it was ever known before” and the latter “two or three feet higher than in the great flood of February 1831”. However accompanying descriptions suggest that the flood of 1839 was neither as high as 1963 nor significantly higher than 1878. The only flood which may have exceeded that in 1963 occurred in November 1761 as indicated by descriptions of the extent of flooding in the town centre; the evidence however, is inconclusive.

Historical evidence therefore places the 1963 flood as either Rank 1 or Rank 2 since the mid-eighteenth century, say 250 years, suggesting a Gringorten plotting position of 450 years (if Rank 1) and 160 years (if Rank 2). Graphical plotting of the 1963 event at these plotting positions and extrapolation of eye-guided lines considerably narrows the range of estimates of the 100-year event from that obtained from

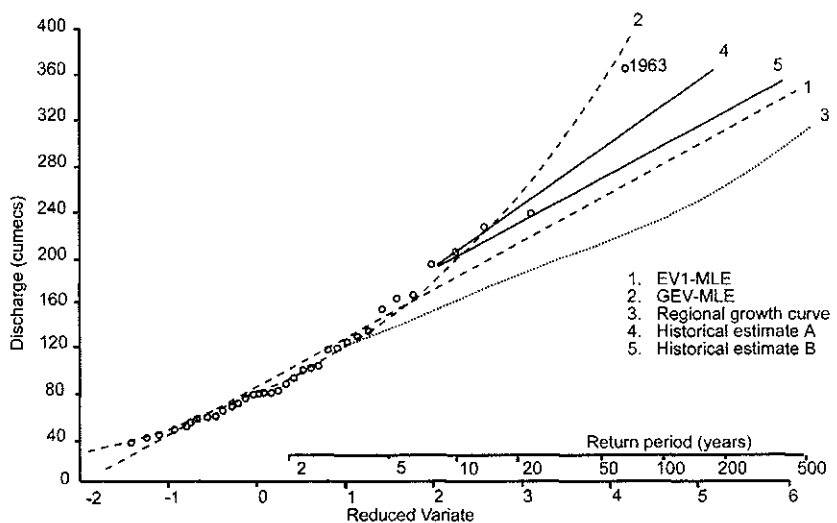


Fig. 3 Flood frequency analysis for the River Wansbeck at Mitford based on gauged data (1 and 2), gauged mean annual flood and regional growth curve (3) and historical data with the 1963 flood as Rank 2 (4) and as Rank 1 (5).

the recorded series (Fig. 3). It demonstrates the value of historical data even where estimation of historical discharges has not been attempted. The regional growth curve is shown to fall well below the data estimates.

River Leam

The River Leam is a tributary of the River Avon with a catchment area of 362 km² (Fig. 2). It is a predominantly rural lowland catchment with its main urban area in the lower reaches at Leamington Spa which is potentially vulnerable to flooding. The gauging station to Eathorpe (catchment area 300 km²) has a 25-year gauged record of annual maxima from 1968 to 1996. The Rank 1 event in July 1968 had a peak discharge of 100.6 m³ s⁻¹, whilst the Rank 2 event had a discharge of 51.6 m³ s⁻¹, a ratio of 1.95. The 1968 event thus plots as a severe outlier (Fig. 4). Application of flood frequency analysis using the distributions and fitting methods listed above suggested that the return period of the 1968 event was between 185 years (GEV-PWM) and 460 years (EV1-MLE). If the gauging station had commenced a year later, omitting the 1968 event from frequency analysis, the return period allocated to the 1968 discharge would have been even greater (1270 years to infinity).

A rapid historical review of flooding was carried out. Limited site-specific survey information on historic floods was located for the River Leam, but there were detailed descriptions of the flooding of buildings and roads which permitted comparisons with the 1968 flood. An annual maximum historic series from 1848 to 1935 was also available for the River Avon at Evesham, with a catchment area of 2200 km². The following events were clearly greater in magnitude at Leamington than the flood of 1968:

- **1932** (21 May) A map report shows that the peak level reached in this event was 0.67–0.85 m higher than 1968. That this event was of much greater magnitude

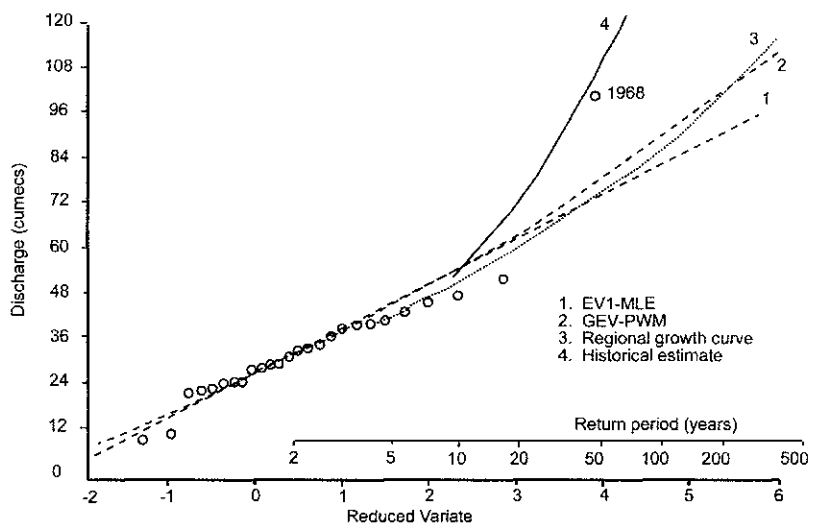


Fig. 4 Flood frequency analysis for the River Leam at Eathorpe, based on gauged data (1 and 2), gauged mean annual flood and regional growth curve (3) and historical data (4).

than 1968 is strongly supported by the reported extent of flooding and levels on roads and in properties.

- **1900** (30 December) No surveyed levels were available in Leamington Spa, but numerous descriptions of depth and extent of flooded properties and streets suggest that levels on the Leam were marginally lower than in 1932. Further downstream at Evesham, the flood was the highest in the historic annual maximum series from 1848 to 1935.

Events of October 1875, 1852, 1848, 1795 and 1735 were probably of greater or equal magnitude to the 1968 flood, but evidence is insufficient to be certain. In addition several events were probably of lower magnitude than 1968, but definitely greater than the Rank 2 event in the recorded data series, including 1947, 1939, 1920, 1882, 1875 (July) and 1867.

On the basis of the above exceedences (definite and probable) of the 1968 event, the estimate of the return period of the 1968 peak discharge may be revised with respect to the Gringorten plotting position (GPP) as follows:

Over the 20th century (1900–1997; 97 years), 1968 is Rank 3	GPP = 38 years
Over the 19th and 20th centuries (1800–1997; 197 years), 1968 is probably Rank 5	GPP = 43 years
Over the period 1735–1997 (262 years) 1968 is probably Rank 7	GPP = 40 years

The historical evidence thus suggests that the return period of the 1968 event was much less than that accorded by flood frequency analysis of recorded data. Without determining the discharge of the historical floods the flood frequency plot may be amended to place the 1968 event discharge at (say) 40 years and the curve extrapolated to higher return periods. Whilst extrapolation is subjective, resulting estimates will clearly be of much greater reliability than objective procedures based on the gauged record only.

The above analysis was carried out in late 1997 but the associated analysis to determine the 100-year flood level through the reach had not yet been assessed when the catchment was affected by a very severe flood in April 1998. Levels in 1998 were significantly greater than in 1968 and were probably in excess of levels achieved in 1932. This event provided further evidence (if it were needed) of the unexceptional return period of the 1968 flood.

DISCUSSION

The Rivers Wansbeck and Leam illustrate the value of including historical information in flood estimation. They also show the uncertainties associated with the use of such information and the need for historical as well as hydrological judgement in the use of historical material. Examples of such judgement are as follows.

- (a) What is the time period in which floods over a threshold have occurred? Alternatively what is the earliest date at which a flood occurrence would have been confidently identified and described with sufficient detail to assess its magnitude? Hirsch & Stedinger (1987) indicated the importance of such assessment, but it is more critical for the Rank 1 flood (e.g. Wansbeck) than for lower ranked flood (e.g. Leam). Such identification depends on the quality of sources and the thoroughness of the search, and the judgement is primarily historical!

- (b) With respect to individual events, how is one to judge the credibility of reported comparisons with previous floods? Judgement is primarily based on an appreciation of historical sources. For example, the local newspaper office in Morpeth was situated in the area at risk from the Wansbeck and is thus considered highly reliable.
- (c) How is one to judge the value of information reported from sites outside the reach of interest especially if above or below a tributary confluence? Examples are for the Leam where more comprehensive information is available downstream from the confluence with the Avon. Experience of the typical concurrence of flooding during the period of the gauged record combined with a knowledge of flood effects on neighbouring catchments for the event in question can assist in making a hydrological judgement.
- (d) What changes have occurred in the channel such that historical observed levels represent quite different discharges from the present. This requires appraisal of man-made changes to bridges and weirs, gravel extraction, and natural incision or deposition.
- (e) Have changes in land use such as urbanization, agricultural drainage or reservoir construction affected runoff response to the extent that the assumption of stationarity is invalidated? When such changes have occurred, the historical period may be split and assessment limited to the most recent period.

CONCLUSIONS

Statistical treatments of historic flood data that exclude description and discussion of the historical and hydrological judgements outlined above can obscure the uncertainties in derived design discharges. They have the appearance of objectivity but conceal many subjective decisions. Historical gauged discharges are likely to be inaccurate and are often unknown.

Often all that is known (and that imperfectly) is that in N years, a threshold Q_0 was exceeded k times. Such data were described as binomial censored data by Stedinger & Cohn (1986) who proposed a treatment using maximum likelihood estimators and showed that the method performed nearly as well as for censored data where the historical discharges are known. Stedinger & Cohn's alternative derivation for censored data was extended by O'Connell *et al.* (1998) who proposed a Bayesian approach to the incorporation of historical and palaeohydrological data. Event discharges are determined to be within a range described by an upper and a lower bound and optionally a proportionally higher likelihood for some point within the interval. Whilst such approaches are the most useful ones available for detailed scheme analysis, the graphical procedure described above based on exceedences of the maximum recorded flow, provides a practical and rapid means of improving upon estimates based on recorded flows alone whilst acknowledging uncertainties in the data.

Compared with conventional hydrometric sources, historical data can be acquired at little expense. The British Hydrological Society has embarked on the creation of a "Chronology of British Hydrological Events" with public access on the worldwide web at <http://www.dundee.ac.uk/geography/cbhe>. At present this depends on voluntary additions: there is a strong justification for a national well-funded programme of collation of such data.

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