Centre for
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NATURAL ENVIRONMENT RESEARCH COUNCIL

# The use of historical data in flood frequency estimation

Report to MAFF

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# Executive Summary

Flood studies regularly require the estimation of the peak discharge for a specified return period that is substantially longer than the available gauged record. Historical data can be used to augment a flood frequency analysis by providing information on floods that pre-date the period of systematic gauging.

This report gives guidance on locating and evaluating historical flood information. It reviews methods for incorporating historical data into flood frequency estimates and includes a case study that serves to illustrate the procedures described.

The benefits of extending the relatively short gauged records that exist for most rivers in the UK, using historical flood data, are briefly discussed in the introduction (Chapter 1). The review of historical information can lead to a better understanding of the factors that lead to extreme flood events. The analysis of information on historic floods can also provide better insight into the seasonality of flood occurrence and the effects of land-use change on catchment flood regime. The chapter concludes by introducing the concept of reviewing flood frequency estimates through the incorporation of historical data.

The prospect of looking for information on flood events that occurred decades, or even centuries, before systematic river flow gauging became established, may appear daunting. Chapter 2 gives guidance on those sources most likely to provide useful data.

The format and reliability of historical flood data are likely to be extremely varied. Chapter 3 encourages a systematic and rigorous evaluation of all historical information gathered. The evaluation, according to completeness and authenticity, is recorded in a simple tick-box procedure.

The review of methods for incorporating historical data into flood frequency estimates (Chapter 4) is relatively wide ranging. It considers the use of paleoflood data as well as historical data, and refers to some of the formal and informal methods that have been suggested for incorporating historical data into flood frequency estimates. Key issues surrounding the use of graphical methods are summarised and comments on the options that appear most useful are made.

A case study – the River Avon at Evesham – is used to illustrate the guidance given (Chapter 5). Historical flood data are collated from a number of sources. A rigorous evaluation of the information, in terms of completeness and authenticity, is undertaken using a tick-box procedure. Flood frequency curves are constructed using the site and pooled analysis procedures described in the Flood Estimation Handbook, and are subsequently reviewed using historical flood information.

Chapter 6 provides a brief discussion of the research and the guidance given. The Report concludes by presenting the principal historical datasets, used in the case study, in Appendices A to H.

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# 1 Introduction

## 1.1 SYSTEMATIC RIVER FLOW GAUGING IN THE UK

The systematic measurement of river flow in the UK formally began in the late 19$^{th}$ century with gauges on the Thames at Teddington and the Lee at Feildes Weir. However, not until the Water Resources Act 1963, did the number of sites recording river flow begin to grow rapidly. The Act gave tremendous impetus to river gauging and in the three years between 1963-1965 over 100 new monitoring stations came into operation (Lees, 1987), with the expansion of the network continuing until the mid-1970s when nearly 800 gauges were operating (DoE, 1983). In international terms, the UK has a dense network of gauges but, put in historical perspective, the lengths of formally gauged river flow records are relatively short. For example, the mean length of the annual maximum flood peak records, available to the research team working on the Flood Estimation Handbook, was 23.4 years (Bayliss, 1999a).

## 1.2 BENEFITS OF HISTORICAL REVIEW

Information on floods that pre-date the comparatively brief formal records that exist for most rivers can usually be found (see Chapter 2). The extension of gauged flow records using historical flood data can be seen to have a number of benefits.

### 1.2.1 Flood-producing mechanisms

The review of historical information can lead to a better understanding of the factors that lead to extreme flood events. There may be a preconception that major floods only occur when certain conditions are evident (Reed, 1999). Local folklore may have it for example, that the largest floods only occur when snowmelt and heavy rainfall combine, or that the occurrence of a major event on a permeable catchment always follows a period of prolonged antecedent wetness. Evidence unearthed as part of a review may do much to confirm or dispel these beliefs. A review of 'The Great Till Flood of 1841' by Cross (1967), using contemporary newspaper reports and local accounts, revealed that the disastrous flooding of that 'chalk-fed' Wiltshire bourne, followed a combination of rain, melting snow and frozen sub-soil.

### 1.2.2 Land-use change and flood seasonality

McEwen (1990) describes how historical flood information was used to assess the effects of land-use change on catchment flood regime. In this example, a combination of anecdotal records and data recorded by contemporary observers during the latter half of the 19th century provided useful information on the impact of hill drainage on flood flows in the Tweed basin. The seasonality of flooding based on data taken from an extension of the gauged record back to the 18th century for two rivers in the basin, and to the early 1880s for two others, is also discussed. Interestingly, the historical flood data indicates that on the River Tweed many of the more extreme events occur in August, in contrast to the gauged record, which shows winter as the dominant flood season.

### 1.2.3 Flood frequency analysis

Flood studies regularly require the estimation of the peak discharge for a specified return period that is substantially longer than the available gauged record. Typically the estimation of the peak for the 100-year return period event is based on a gauged annual maximum series less than 25 years in length. The formally gauged record represents a relatively small sample of a much larger population of flood events, and may be unrepresentative, particularly if it comprises a 'flood-free' or 'flood-rich' period. The Flood Estimation Handbook gives guidance on how to effectively extend these relatively short records by pooling data from catchments that are hydrologically similar (Reed *et al*., 1999; Jakob *et al.*, 1999).

An alternative approach is to extend the period of record through the incorporation of historical flood data. In 1988 two large floods occurred on the River Kenwyn at Truro in Cornwall that were far in excess of anything recorded in the gauged record from 1968. Acreman and Horrocks (1990) show how the use of information on historic floods, based on the methodology described in the Flood Studies Report (NERC, 1975), gave greater confidence in the assessment of the rarity of the two events, than that using the relatively short gauged record alone. Archer (1987) provides a further example of how historical flood information has been used to improve flood frequency estimates. Historic discharges from 1771 for the River Wear at Durham were estimated and used to extend the gauged record that began in 1958. After fitting flood frequency curves to the gauged data, and a number of combinations of gauged and historical data for different periods, Archer concludes that the use of the gauged flood series alone was likely to lead to a serious underestimation of the risk of flooding.

The incorporation of historical data into flood frequency estimates has been the subject of considerable debate in the literature (e.g. Hirsch, 1987; Hosking & Wallis, 1986a; Sutcliffe, 1987). The use of paleoflood techniques has also received considerable attention, particularly in the USA (e.g. Baker, 1987; Stedinger *et al.*, 1992). A review of the extensive literature available, written for the practitioner, should greatly assist those wishing to assess the preferred flood frequency curve produced by conventional analysis in the light of historical information.

# 2 Locating historical flood information

## 2.1 INTRODUCTION

The collation of flood information that pre-dates the relatively short gauged records that exist for most catchments is seen to be highly desirable (Chapter 1). The assimilation of such data often requires a meticulous approach that, in conclusion, can be both productive and rewarding. Indeed, Archer (1999) takes the view 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.”

The prospect of looking for information on flood events that occurred decades, or even centuries, before formal river flow gauging became established, may appear daunting. However, Potter (1978), in ‘The use of historic records for the augmentation of hydrological data’, provides detailed guidance on the type of hydrological information that can be obtained and how to find it. Although he describes how data may be found relating to events that occurred before the Norman Conquest, he also states that searching for information on floods that occurred before the early 18$^{th}$ century is only likely to reveal highly descriptive accounts that “produce only some vague idea of the occurrence of earlier floods”.

The guidance given here relates primarily to sources that are likely to give useful data on floods occurring from the early 1700s. Public Record Office collections, diaries, chronicles, estate records, parish registers and other ecclesiastical records are examples of sources that may provide information, and those wishing to learn more of these potential sources in their search for information on events that took place before the 18$^{th}$ century, are referred to Potter. In Scotland, there are differences in institutional and cultural history, and the way archived material is organised. For those wishing to establish a historic flood chronology for a Scottish river, McEwen (1987) gives an insight into those sources of information that may be particularly relevant north of the border.

## 2.2 GAUGING AUTHORITY RECORDS AND ARCHIVES

In addition to what is likely to be a relatively short formal gauged flow record, regional offices of the Environment Agency (EA) and the Scottish Environment Protection Agency (SEPA) may have informal data that usefully extend the record. This may be a level-only record resulting from a daily-read gauge board established at or near the gauging station before the formal flow records began. Additionally, the Agencies or their predecessor organisations, may have records of levels taken at nearby mills, sluices or locks.

Potter (1978) points out that the Water Authorities, and before them the River Authorities, River Boards, Catchment Boards and River Conservancies, would often produce a report following a major flood event, or commission consulting engineers to do so. This still holds true today and reports on many of the more recent 20th century floods are likely to be held at EA offices. Significantly, these reports often include a historical review of floods that have occurred on the river in question. For example, a report commissioned by the North East Region of the EA on flooding on the river Ure in North Yorkshire, includes a thorough review of historical flooding at Boroughbridge (Wallingford Water, 1998). Similarly, the review of the Easter 1998 floods that affected much of the English Midlands, undertaken by Bye and Horner (1998) on behalf of the EA, contains useful data in Volume 2 that were included to try and put the floods in historical perspective. Reports of this nature may also be located at the offices of County or District Councils, Internal Drainage Boards and others that have responsibilities in flood defence or drainage.

Anecdotal evidence of flooding may also be held. Contemporary cuttings from newspapers often provide useful information and collections may be found in archive material. Archer (1992) in his book ‘Land of Singing Waters’ remarks on the value of interviews conducted by gauging authority staff with those affected by flooding. Records of these interviews may be found through contacting local EA offices.

In summary, it may be relevant to note that in reference to the historical flood data that appears in Volume IV of the Flood Studies Report (NERC, 1975), Jones (1975) comments that “The gauging authorities had usually assembled a file of such information…”. In many cases, therefore, the relevant gauging authority will be able to provide at least some historical flood information for the river of interest and, in some cases, be the primary source of such data for events that occurred in the 20th century.

## 2.3 FLOOD MARKS AND STONES

Peak levels of major flood events have been recorded in a variety of ways over the centuries. At Worcester Cathedral a stone wall is engraved with the dates and levels of historic floods that have occurred on the River Severn (Damari, 1995). At Skenrith Corn Mill on the River Monnow in Wales, flood levels have been recorded back to 1928, both informally on a door and carved in the building’s wooden timbers (Bye & Horner, 1998).

A plaque on the wall of No. 18, in Stratford-Upon-Avon’s Waterside, records the relative height of the 1901 and 1932 floods. Here someone has had the foresight to record the peak level of the Easter 1998 flood with a hurriedly-drawn chalk mark, during or immediately after the event (Plate 2.1). Without this intervention, this valuable information could easily have been lost.

Archer (1992) provides an example of the value of flood stones. Along the River Tyne in Northumbria, five flood stones recording the height of the truly exceptional 1771 flood have been located and seem generally consistent. If just one flood stone had been found, then the level recorded might have been barely credible.

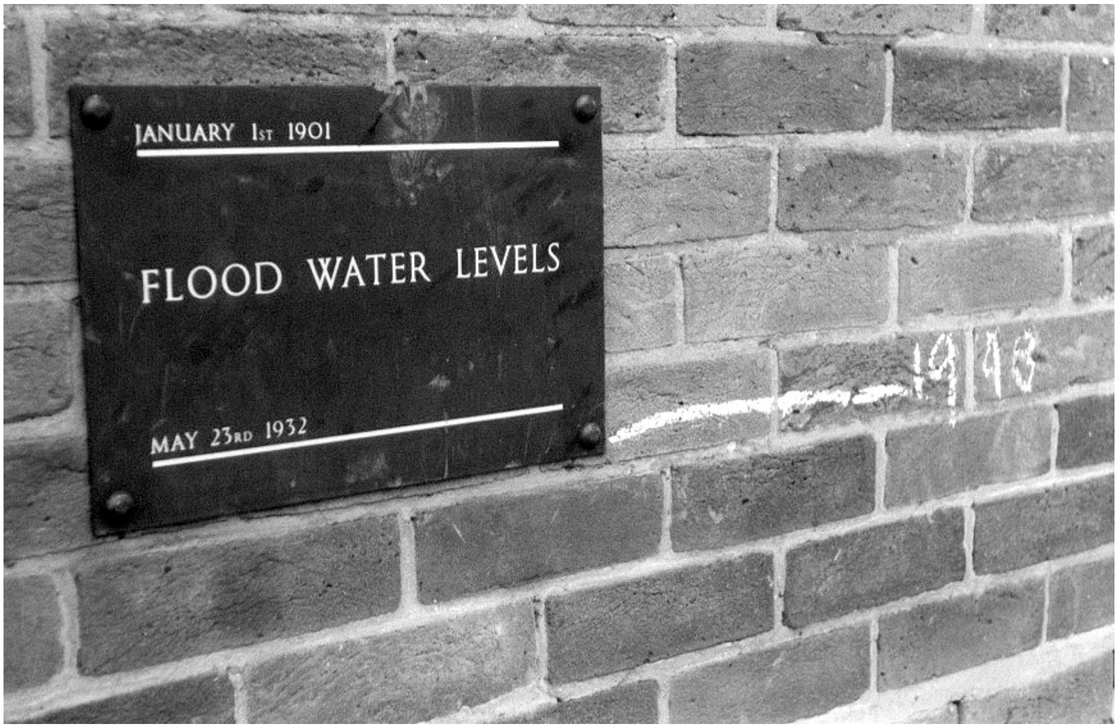



***Plate 2.1*** *Flood plaque on the wall of No. 18, Waterside, Stratford-Upon-Avon, Warwickshire (Photograph taken 25/4/1998)*

Of particular value are occurrences where the relative heights of more than one flood are recorded in the same location, since they portray a tangible ranking of the flood events shown. However, flood stones may not always be accurate in the information they convey. Both the dates and levels may on occasion be erroneous, particularly if the stone has been added long after the event occurred, or if the structure has been rebuilt. Further research may be needed to corroborate the data they provide. Nevertheless, in most cases these marks and stones do provide valuable information. Descriptions of these flood marks can often be found in 'local histories'. Ancient bridges and riparian buildings may bear flood marks and stones, and are worthy of inspection.

## 2.4 PERIODICAL LITERATURE

### 2.4.1 Scientific, academic and engineering journals

Examination of contemporary scientific, academic, and engineering publications is often worthwhile. Table 2.1 indicates those journals most likely to provide historical information on flooding, along with details of the period covered by the publication and changes in title.

| | |
|---|---|
| 1837 - 1896 | Proceedings of the Institution of Civil Engineers |
| 1896 - 1946 | Transactions of the Institution of Water Engineers |
| 1947 - 1974 | Journal of the Institution of Water Engineers |
| | |
| 1860 - 1899 | Symons's British Rainfall |
| 1900 - 1966 | British Rainfall |
| | |
| 1866 - 1901 | Symons's Monthly Meteorological Magazine |
| 1901 - 1920 | Symons's Meteorological Magazine |
| 1920 - 1993 | The Meteorological Magazine |
| | |
| 1872 - 1884 | Quarterly Journal of the Royal Meteorological Society |
| 1884 - to date | Journal of Meteorology |
| | |
| 1953 - to date | Weather |
| | |
| 1865 - 1910 | Scottish Journal of Meteorology |

***Table 2.1*** *Journals most likely to provide historical flood information*

A paper given by Symons on 29 February 1876, published in the 'Proceedings of the Institution of Civil Engineers' (1876), indicates the type of information that may be found in journals of that era. In his description of the July 1875 floods that affected much of Central England, he gives details of rainfall recorded across Wales and the Midlands and then goes on to list flood levels observed on the rivers Cherwell and Warwickshire Avon. Of particular value is his comparison of these observations with other historic flood levels witnessed at the same locations.

Publications primarily concerned with rainfall and meteorology may also make reference to historic flood events. 'Symons's British Rainfall 1894' devotes 15 pages to the floods that occurred in October and November of that year. Many of the references to the flooding are purely descriptive but for some locations more factual information is given. For example, it was reported that on November 15$^{th}$ the Thames at Shillingford in Oxfordshire "*was higher than any other flood since 1768, except that of January 27$^{th}$, 1809*". There may also be reference to other contemporary publications. That same 1894 edition (published in July 1895) also notes that the flooding that affected the Thames Valley and the West of England had already been dealt with by papers put before the Royal Meteorological Society. Following up this lead, examination of contemporary issues revealed two papers relating to the floods of 1894. A most comprehensive report by Symons and Chatterton (1895) compares the November 1894 flood with others recorded on the Thames, and even gives a flood chronology back to 9 AD. Secondly, a paper in the society's journal by Southall (1895) not only describes the 'Floods in the

West Midlands' that occurred during 1894, but gives comparative heights of flood peaks going back to the late 1700s for a number of sites.

Examination of the contents page for British Rainfall yearbooks will sometimes turn up the type of coverage described above. More typically perhaps, the 'heavy rainfall' sections are more likely to include comments on floods. They will also provide dates when rainfall totals were high, which can then form the basis of a search elsewhere.

Potter (1978) also cites two engineering journals – the 'Engineer' (dating from 1856) and 'Engineering' (dating from 1867) – as potential sources of historical flood information. In addition to these he also lists the professional and trade journals, 'Proceedings of the Institute of Transport', 'Surveyor', 'Municipal Engineer' and 'Water Services'. The institutions concerned will hold collections of these journals in their own libraries. Copies may also be obtained through the British Library.

### 2.4.2 Gentleman's Magazine

The 'Gentleman's Magazine' comprises a miscellany of information about people, places and events. Published monthly from 1731, it can provide information on floods, particularly until the 1830s, when the content of the magazine began to change. The magazine covered events occurring throughout Britain, but there was a tendency for reports to focus on London and surrounding counties. Although the information contained therein is generally of a descriptive nature, these early volumes are especially useful given the paucity of newspaper coverage at that time (Potter, 1978).

An initiative under the auspices of the Electronic Libraries programme has seen substantial runs of 18$^{th}$ and 19$^{th}$ century journals scanned and indexed. The 'Internet Library of Early Journals' provides Internet access to volumes covering at least 20 years, for six publications produced during that era (www.bodley.ox.ac.uk/ilej). Gentleman's Magazine for the period 1731-1750 can now be searched and viewed electronically. If the programme is deemed successful, after an evaluation of the frequency and purposes to which the data are put and the acceptability of indexes and images to users, then this project may form the basis for the development of a national digitisation programme for out-of-copyright journals.

## 2.5 NEWSPAPERS

### 2.5.1 History

Before the deposition of James II in 1688, printing had largely been rigorously controlled and newspapers suppressed, except that is for those publishing government statements. The period following the 'glorious revolution', which brought William III to the throne, saw the freedom of the press established and the first independent newssheets printed in

London and the Provinces. The year of 1690 marks the first publication of the newssheet that was to become Berrow's Worcester Journal, reputed to be the oldest surviving newspaper in the world. It was not until the 1740s that local news, rather than national events, began to be featured. Flood events were covered in considerably more detail in the newspapers prior to World War 1 than they were in post-war Britain (Potter, 1978). However, more recent events, such as that which occurred at Easter in 1998 and the extensive flooding of October and November 2000, have received considerable attention from the press.

### 2.5.2 Local newspapers

These extracts from the Stratford-Upon-Avon Herald for January 4$^{th}$ 1901, reporting on the 'New Century flood' that had occurred some three days earlier, provide examples of the coverage that flood events often received in the local press. Much was said of escapes and rescues, and the effect of the floods on daily routine.

> *"Those who wished to reach their residences had either to take advantage of passing vehicles or of a punt that was diligently plying in the neighbourhood. Milk floats, too, were in requisition, and these were sometimes so crowded that there was a risk of the passengers coming to grief by reason of the horses' restiveness, and thrown into the rising waters."*

The highly descriptive nature of the reporting was typical of that period, and did much to convey the nature and mood of the event. Additionally, there was often more factual information given as to the severity of the flooding.

> *"At Stratford-on-Avon the water rose with unprecedented rapidity, and the deluge which followed was a record one, the water rising some seven inches higher than on the occasion of the historic flood of 1801. It may be interesting to record that the four succeeding severe floods within the precincts of the borough occurred on October 25$^{th}$, 1882, July 22$^{nd}$, 1885, February 6$^{th}$, 1897, and October 1$^{st}$, 1848."*

An important feature of newspaper coverage of flood events of this era was the reference to earlier events and, in some instances, the comparison of relative flood height. This information is often vital if a ranked flood series is to be produced and local newspapers can be often be the primary source of information of floods that occurred during the 1800s and early 1900s.

Public lending libraries will usually maintain a collection of local newspapers. Early issues are often microfilmed to protect the collection, and where this has been done this can speed up the search for flood information. Assistance may also be forthcoming where the newspaper or the library has provided a summary or index of major events that occurred during the year. Nevertheless, the inspection of an entire collection is a time-consuming and laborious process, so in practice the inspection of local newspapers often follows a lead discovered elsewhere.

### 2.5.3 National newspapers

National newspapers tend to give less detail about flood events than the local press but may be useful in indicating that an event did occur and is worthy of investigation elsewhere. 'The Times' has been indexed since 1790. The printed indexes allow relevant articles to be identified but can be time-consuming to use. A recent advance is the availability of 'Palmer's Index to The Times (1790-1905)' and the 'Official Index to The Times (1906-1980)' in electronic form. For those wishing to examine articles from The Times without visiting one of the national collections, access by subscription through the World Wide Web to 'Palmer's Full Text Online' (www.chadwyck.co.uk/products) is now available. There is a fully searchable electronic index linked to a high quality scanned image of the selected article. With access to over 25000 issues published between 1785 and 1870, this is a major resource.

## 2.6 THE WORLD WIDE WEB

Never before has there been so much data at our fingertips. The advent of the World Wide Web (WWW), and the huge growth in the number of people able to gain access to the WWW via an Internet connection from their PC, has meant that this is rapidly becoming a major resource for those wishing to find historical flood information.

A major development has been the establishment of the British Hydrological Society's 'Chronology of British Hydrological Events' (www.dundee.ac.uk/geography/cbhe). This site encourages those with data relating to hydrological events occurring up to 1930 to submit this information for inclusion on the database. There is an online data entry form available for this purpose. Contributors are encouraged to quote only from reliable sources, such as contemporary newspapers, and to ensure that the source is out-of-copyright or that they have the relevant permissions. With over 6000 entries to date, the site has already become an important resource for those seeking to establish a chronology of floods.

In addition to providing access to electronic versions of early newspapers (Section 2.5.3), and websites such as that described above, powerful search engines that are available on the WWW can unearth useful information and sites. For example, a search on the keywords 'Great Flood Warwickshire' using the search engine 'Google' found an index of magazine articles on the Alcester and District Historical Society website. This led to the discovery of a contemporary description of the flood that brought such havoc to the town on January 1$^{st}$ 1901. Different search engines will bring different results from the same keyword and, typically, for every piece of value there will be an awful lot of unwanted information. However, guides on using search engines are freely available and with experience these searches become more fruitful.

# 3 Evaluation of historical flood information

## 3.1 INTRODUCTION

The format and reliability of historic flood data found for a particular river or reach are likely to be at least as varied as the sources from which they derive. If the collated information is to lead to an *improvement* in the flood frequency estimates based on relatively short formally gauged records alone, then a rigorous evaluation of the historical data should be undertaken. Without this review it is likely that much spurious information will be included, to the detriment of the estimates produced.

## 3.2 FORMAT

The format of information on historic flood events that preceded the systematic measurement of river flow is likely to vary tremendously. A description in a contemporary diary may convey a vivid image but record only the year of the event. Some accounts, such as that recorded in the Welford-on-Avon parish register, and reproduced in part below from a compilation by Savage (1929), may give the day, month and year of the event, and give hints regarding the severity of the event.

> *"The xviij$^{th}$ of July anno Domini 1588 in the morning there happened about viij of the Clocke in Avon such a sudden floode, as carried a way all the hey a boute Avon and did much harme; yt was higher then ever yt was knowne by a yeard & a halfe and something more; owlde ffather Porter buried about iiij yeares past being then a hundred and nyne yeares of age never knew yt soe highe…"*

The compilation of historical flood records presented in Volume IV of the Flood Studies Report (NERC, 1975) provides an example of contrasting format to that given above, illustrated by the list of historic floods given for the Wye at Belmont.

*55/2 Wye at Belmont*

| | | | | |
|---|---|---|---|---|
| *11.2.1795* | *52.30 m* | *1080* | *cumecs* | *Wye River Board. Reference Book, Vol.2, 1955. Levels of major floods recorded at Old Wye Bridge.* |
| *6.2.1852* | *51.80* | *892* | | |
| *19.12.1869* | *51.08* | *651* | | |
| *1.1.1892* | *50.81* | *566* | | |
| *15.11.1895* | *50.88* | *595* | | |
| *22.1.1899* | *51.16* | *680* | | |

From records primarily assembled by the gauging authorities, peak levels, and in some cases estimated flows, are provided in tabular form. Details of sources are given along with other pertinent information, and for the longer records, floods may be ranked according to magnitude.

The usefulness of data derived from these different formats will vary considerably. Early historical records will tend to be far more qualitative than those of more recent times, but can nevertheless provide information of value.

## 3.3 AUTHENTICITY

### 3.3.1 Introduction

Section 3.2 illustrates how information on flooding collated from historical sources is likely to be in a range of formats. Such information also tends to be of varying reliability. The importance of establishing the authenticity of historical data used to extend the effective length of record for the Rivers Wansbeck and Leam is noted by Archer (1999), who observes that there is a need for both historical and hydrological judgement in the use of such information. McEwen (1987), in describing sources likely to assist in establishing a historic flood chronology for Scottish rivers, categorises sources into those that are 'authenticated' and those that are of 'variable reliability'. This categorisation of historical sources in Scotland is likely to have been based on judgement and experience rather than any formal procedure.

### 3.3.2 Source analysis

Compilations of references to weather events and related phenomena have been heavily relied upon by those researching the climate of the Middle Ages (500 – 1500 AD). Universal chronicles, for example, were produced throughout this period, but since the chroniclers were often unable to distinguish fact from legend, the documents frequently contain erroneous and misleading information (Bell & Ogilvie, 1978). Early in the 19$^{th}$ century, historians began to question the validity of such documents and developed procedures known as 'source analysis'. Prior to this, critical review of sources of information was virtually unknown. Even with a growing awareness amongst historians of the need for a more rigorous approach, many compilations have been produced in more recent times, without due regard to these needs.

The application of a detailed source analysis to historical documents produced in the Middle Ages is likely to require particular skills, such as a knowledge of Latin, and be beyond most 'flood studies'. The methodology, nevertheless, can be applied to sources more commonly used in historical flood research such as 'local histories' and newspaper articles. The procedure is complex, but the basic principles of source analysis – as outlined by Ingram *et al*. (1978) and Bell and Ogilvie (1978) – are summarised here as a number of questions that need to be answered if the information is to be used with confidence.

- How motivated and qualified was the writer to record the events accurately?

  Did the author have reason to fabricate or exaggerate the details of the event?

  Did the writer live close in space and time to the events he/she is describing and record them within a short time, or, did he/she have access to first-hand oral or written reports and accurately derive information from them?

- Is this an independent account of the event or is it essentially derivative?

  Derivative material frequently includes transcription errors. Compilations or syntheses, based on other derivative documents, often retain any errors present. Historians have found that independent accounts tend to provide different descriptions of the same event, while an account based on another often has obvious similarities.

## 3.4 EVALUATION

Historical flood information is likely to be varied both in format and reliability. An evaluation of this information is crucial if spurious data are to be identified and rejected. The scrutiny of data relating to historical floods is likely to involve both historical and hydrological judgement but the examination can be made more rigorous if a systematic approach is undertaken.

The graphical methods described in Section 4.5 require that the flood series be ranked, so that the plotting position can be calculated using a formula such as Gringorten's (Gringorten, 1963):

$$p_i = i^{\text{th}} \text{ plotting position} = (i - 0.44) / (n + 0.12)$$

where $i$ is the position in the ranked (descending) order, $n$ is the period to which the ranking relates and $p_i$ is the exceedance probability. It is necessary therefore for the variables $i$ and $n$ to be defined with reasonable confidence, if the historical flood information available is to be used in this procedure. As a consequence, any systematic evaluation needs to focus on this requirement.

The following questions will need to be asked:

- Does the information found really relate to the site of interest? Ideally the information will specifically name the tributary and location you are interested in, but on occasions only the river basin or district will be given.

- Is there sufficient information to be reasonably certain when the event occurred? This will need to be established, so that the historical period to which the flood series relates can be defined.

- Can the peak flow or level be established? This enables the flood series to be ranked, although this can sometimes be achieved without this information. Reports on flooding occasionally include information that assists in the ranking of historic floods, without specifying the flood level or flow (e.g. the 1901 flood was 6 inches higher than the 1801 event). The peak flow, or at least an estimate, is also needed for the event to be positioned on the extreme value plot (Section 4.5).

Data relating to each historic flood can be evaluated according to the completeness of the information and its authenticity, by using the tick boxes shown in Table 3.1. The authenticity weighting is based on the source analysis described in Section 3.3.2.

| | Where? | | | When? | | | Magnitude? | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ref. | River basin | Tributary | Location | Year | Month | Day | Ranking possible? | Level | Flow | Authenticity weighting? |
| 1 | | | | | | | | | | |
| 2 | | | | | | | | | | |
| 3 | | | | | | | | | | |
| 4 | | | | | | | | | | |
| 5 | | | | | | | | | | |
| 6 | | | | | | | | | | |
| 7 | | | | | | | | | | |
| 8 | | | | | | | | | | |
| 9 | | | | | | | | | | |
| 10 | | | | | | | | | | |

***Table 3.1*** *Tick boxes*

It is important to establish that the events described relate to the site of interest. It is not necessarily essential to determine the exact date the flood occurred, although this will assist in the search for historical information. Establishing the year of occurrence may be sufficient to identify the period to which the ranked historical flood series relates.

The completeness of the historical data relating to the magnitude of the flood event however, has a direct bearing on the usefulness of that information. Ranking may be possible without flood peak level or flow data, but a peak flow will need to be estimated if the event is to be included in a flood frequency analysis. The availability of flood peak level data will increase the reliability of the ranking and allows a considered estimate of flow to be produced. Historical information that includes both level and flow data is likely to be seen as the most valuable, although the reliability of such information should be ascertained before use.

It is recommended that all the information collated for each historic flood event should be assessed using the ‘source analysis’ methodology described in Section 3.3.2. The authenticity of such data is likely to vary considerably. A weighting that reflects this variability in reliability could be recorded in the relevant column on the tick-box sheet (Table 3.1) where:

(a) no tick – the information is unreliable and should not be used
(b) single tick – the information is reliable
(c) double tick – the information is very reliable.

Where information from a number of sources has been collated for an historic flood the authenticity weighting recorded should relate to the most reliable source.

Section 4.5 describes the review of the flood frequency curve by plotting the largest floods taken from the combined historical and gauged records. Typically in the use of this method one symbol size and shade is used to depict all data. To reflect the variability of the completeness and authenticity of the historical data, recorded during the evaluation procedure, the use of symbols of different 'visual weight' is suggested. A scheme is given below (Box 3.1) but this can be tailored to the plotting software being used.

***Box 3.1*** *Symbol scheme*

Suggested symbol scheme to give greatest weight to those historic flood events with complete magnitude information and judged to be from a highly reliable source. Floods taken from the gauged record are, in this context, considered to be from a 'very reliable' source and in most cases magnitude information will be complete.

| Completeness of magnitude information | Authenticity weighting | | |
|---|---|---|---|
| | Unreliable | Reliable (✓) | Very reliable (✓✓) |
| 1. Ranking possible but no flood peak level or flow data available. Flow guesstimated. | | △ (small) | ▲ (small) |
| 2. Ranking possible and flood peak level available. Flow estimate based on level. | | △ (medium) | ▲ (medium) |
| 3. Ranking possible. Flood peak flow estimate available. | | △ (large) | ▲ (large) |

# 4 Incorporating historical data into flood frequency estimates

## 4.1 INTRODUCTION

Volume 1 of the Flood Estimation Handbook (Reed, 1999) encourages the exploration of historical flood data and recommends their informal incorporation into flood frequency estimates. Appendix C of that volume implies that formal methods of incorporation are currently impractical. The principal reason given is that "… the preferred estimate of flood frequency – with which the historical data are to be reconciled – is itself likely to be based on a combination of methods."

Informal methods are distrusted by the regulator because of their inherent subjectivity and the possible scope for abuse. The researcher dislikes informal methods because of their neglect of scientific method, and the implication that research has not addressed the practical issues.

This chapter reviews methods for incorporating historical data into flood frequency estimates. It is wide-ranging and, in parts, idiosyncratic. The serious student will want to study key references. The ardent researcher will (as ever) find judgements to disagree with and dimly lit recesses to probe. But this review is principally written for the practitioner. Beyond introducing the subject and pointing to the literature, the chapter takes as its aim the task of exposing the issues involved in incorporating historical data into flood frequency estimates.

The review concludes that the FEH recommendation to use informal graphical methods is reasonable, but adds emphatically that incorporating historical data into flood frequency estimates requires hydrological understanding and statistical care.

## 4.2 SCOPE OF REVIEW

The review is relatively wide-ranging. It considers the use of paleoflood data as well as historical data, and refers to some of the formal methods that have been suggested for incorporating historical data into flood frequency estimates. The review does not however extend to consider methods specifically designed to cater for data series with known gaps.

The review is challenging because:

- There is a large and diverse literature;
- The issues are complex;

- The issues given most exposure have not always been those most important to the practitioner;
- Some aspects have attracted divergent views from high-powered scientists;
- The reader is invariably assumed familiar with relatively advanced statistical concepts, making the subject less accessible to many;
- Some findings are easy to understand (i.e. glorified common sense) whereas others are highly technical or based on detailed assumptions.

The review is presented in three main parts. Section 4.3 adopts something of a reportage style, to introduce the language and facets of historical and paleoflood analyses. By quoting from what others have said, it encourages the reader to think through ideas and options. Some spellings have been anglicised or otherwise unified. Section 4.4 then discusses a series of important issues/choices in greater depth, with the present authors' opinions more to the fore. Graphical methods are considered in Section 4.5. The review concludes with a summary of guidance in Section 4.6.

Some important references will have been overlooked or injudiciously omitted. US sources are widespread in this review and while US research is appropriately advanced in paleoflood methods, it is likely that European research has more to say than reflected here: particularly about the use of historical data. There are outstanding inheritances of flood information elsewhere, most notably for Chinese rivers (e.g. Luo, 1987).

It is hoped that this review touches enough sources to expose the main issues but too few to be mistaken for authority. It is impractical to attempt more within a short-term project. The following is offered as a slogan to encourage the incorporation of historical data into flood frequency estimates. "The analyst's flood estimate is a passing assessment, overridden by today's flood or tomorrow's fad. A river's flood history is forever."

## 4.3 DISPATCHES FROM LITERATURE

### 4.3.1 Historical flood records

"Historical flood records must possess certain features if they are to be used in frequency analysis. The basic requirement is that, for every such flood, one must be able to state its rank as an annual flood within some particular period of time." (Hirsch, 1987)

"The difficulties with evaluating a record are … of two types: … identifying the threshold and … determining which years are in the sample and which are not." (Hirsch, 1987)

Sources and facets of historical data are discussed throughout this report.

### 4.3.2 Paleoflood information

"Paleoflood hydrology is the study of past or ancient flood events which occurred prior to the time of human observation or direct measurement by modern hydrologic procedures." (Baker, 1987)

"Paleoflood information describes the many botanical and geophysical sources of information on large floods which are not limited to the locations of past human observations or recording devices. Botanical data can consist of the systematic interpretation of tipped [i.e. skewed] trees, scars, and abnormal tree-rings along a watercourse providing a history of the frequency with which one or more thresholds were exceeded. Recent advances in physical paleoflood reconstruction have focused on the use of slackwater deposits and scour lines as indicators of paleoflood stages, and the absence of large flows that would have left such evidence. Such physical evidence of flood stage along a watercourse has been used with radiocarbon and other dating techniques to achieve a relatively accurate and complete catalogue of paleofloods in favourable settings with stable channels." (Stedinger *et al.*, 1992)

"Slackwater deposits consist of sand and silt (occasionally gravel) that accumulate relatively rapidly from suspension during major floods, particularly where flow boundaries result in markedly reduced local flow velocities. Tributary-mouth slackwater deposits are among the most easily recognised in a reconnaissance study of potential paleoflood investigations. Bedrock caves are especially valuable for the long-term preservation of flood slackwater sediments." (Baker, 1987)

"Geochronology is the dating of Earth materials by a variety of techniques." (Baker, 1987)

"Radiocarbon dating is the standard tool employed for absolute dating in paleohydrologic work." (Baker, 1987)

"The most useful stratigraphic association for radiocarbon ages is the location of datable materials on the discontinuity surfaces that separate individual flood events." (Baker, 1987)

"The use of multiple sources of historical and paleoflood data for a site or region provides the most comprehensive and accurate reconstructions of the magnitude and frequency of floods occurring prior to systematic records." (Salas *et al.*, 1994)

The term *systematic record* is widely used in the literature to refer to a gauged flood series. This is also sometimes called a *conventional record*.

### 4.3.3 Character of information

"Different processes can generate historical and paleoflood records. A flood leaving a high-water mark, or known to be the largest flood of record from written accounts, is the largest flood to have occurred in some period of time which generally extends back beyond the date at which that flood occurred. In other cases, several floods may be recorded (or none at all) because they exceed some perception [or impact] level … for their occurrence to be noted, or for the resultant botanical or physical damage to document the event. In statistical terms, historical information represents a censored sample because only the largest floods are recorded. To correctly interpret such data, hydrologists should understand the mechanisms or reasons [by which] … historical, botanical or geophysical records document that floods of different magnitudes either did, or did not, occur. The historical record should represent a complete catalogue of all events that exceeded various thresholds so that it can serve as the basis for frequency analysis." (Stedinger *et al.*, 1992)

In the literature, a *censored flood series* often refers to a data record for which occurrences of floods greater than a reference threshold are known but their magnitudes are unknown (or only poorly defined). But see below. A systematic record is a (conventional) record of flood flows obtained by continuous or near-continuous gauging. A historical record is any non-systematic information potentially relevant to judging the frequency of large floods or the magnitude of rare floods.

A systematic record – most often of annual maximum river flows – is generally self-defining. If these flows are known to be the largest drawn from each of $N$ years, it may not matter whether the $N$ years are consecutive or not. In contrast, date information and continuity statements such as "this was reported to be the largest flood observed since 1894" are essential if non-systematic information is to be interpreted effectively.

"Historical and paleological information generally falls into the following categories:
(a) maximum levels, and flows estimated from them, of one or more historical floods;
(b) information that a historical flood did, or did not, exceed some specified level;
(c) information that none of the floods in a certain time interval exceeded some specified level."
(Hosking, 1986)

### 4.3.4 Rating curves

Most river flows are estimated from water-level measurements. The relationship between water level and flow is defined by a rating curve. This may change appreciably over time: both episodically in alluvial rivers and, more generally, over the very long time-scales considered in some paleoflood investigations.

"Slope-area measurements or model testing may be used to extend the rating curve and thus to derive reasonable estimates of peak flows. These techniques are equally applicable when converting historical levels to flows. However, not only will the degree of extrapolation be greater but the additional question of the stability of the site must be investigated in terms of geology and of possible changes in channel geometry." (Sutcliffe, 1987)

"It is important in flood studies to be able to assign a maximum flow and associated error range to the historical flood." (Cook, 1987)

"Uncertainties in calculating peak flow for historical floods may be quite large." (Cook, 1987)

"It is desirable that estimates should be retained in their original units as their precision is often exaggerated by conversion; for example, the Nottingham flood is quoted as … 50,000 ft$^3$ s$^{-1}$." (Sutcliffe, 1987)

### 4.3.5 Censoring

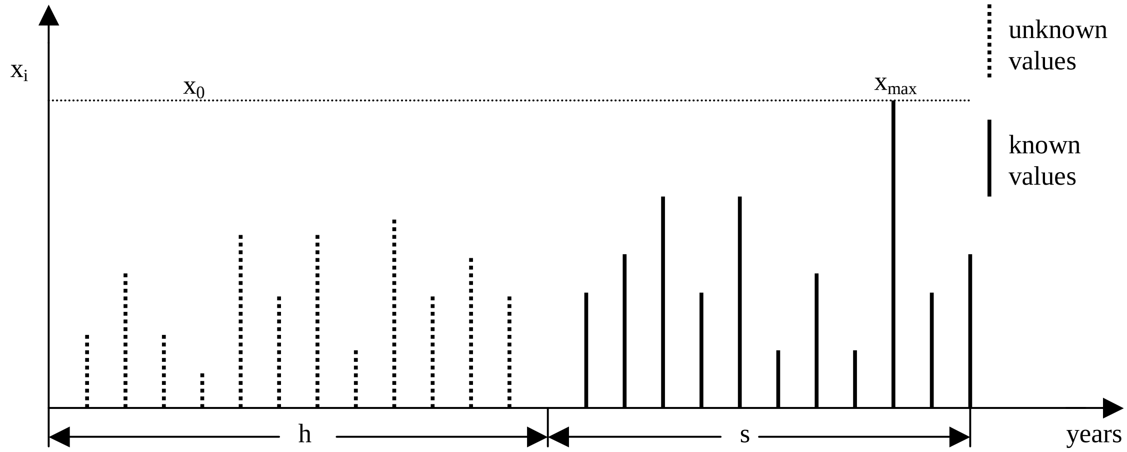
"Historic flood marks are usually found on walls, bridges or on specially constructed flood stones. They indicate the levels of flood that have risen above a fixed point during some historic period. … Values are only specified if they lie on one side of the threshold. Samples that exhibit this property are known as censored samples, the threshold being called the censoring point. If the threshold is fixed, the proportion of censored events is a random variable, and censoring is Type I …" (NERC, 1975, Vol. I, p. 213.)

As introduced earlier, a censored flood series often refers to a data record for which occurrences of floods greater than a reference threshold are known but their magnitudes are unknown (or only poorly defined). Strictly, this is a *binomially-censored* series (e.g. Stedinger & Cohn, 1986): the data indicating to which of two states (peak-above-threshold or peak-below-threshold) each flood belongs. Confusingly, this case crops up in related applications where the magnitudes of *gauged* floods are known when they are below a threshold but not when they are above. This 'missing peaks' problem is outside the scope of this review.

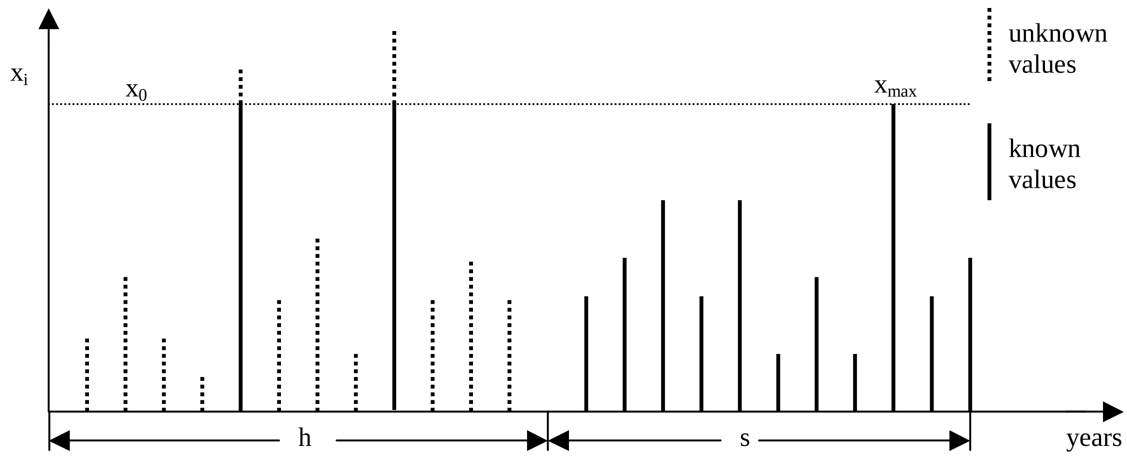
A no less important case is when both the occurrences and magnitudes of floods above a threshold are known, which historical data series defined by flood marks (and some paleoflood analyses) can give rise to.

Censoring cuts both ways. Sometimes – e.g. where there is no systematic record – the analyst looks only at events larger than the threshold. When analysing a censored historical series alongside a systematic record, it has to be remembered that the systematic series sometimes includes values above the threshold defining the historical flood series.

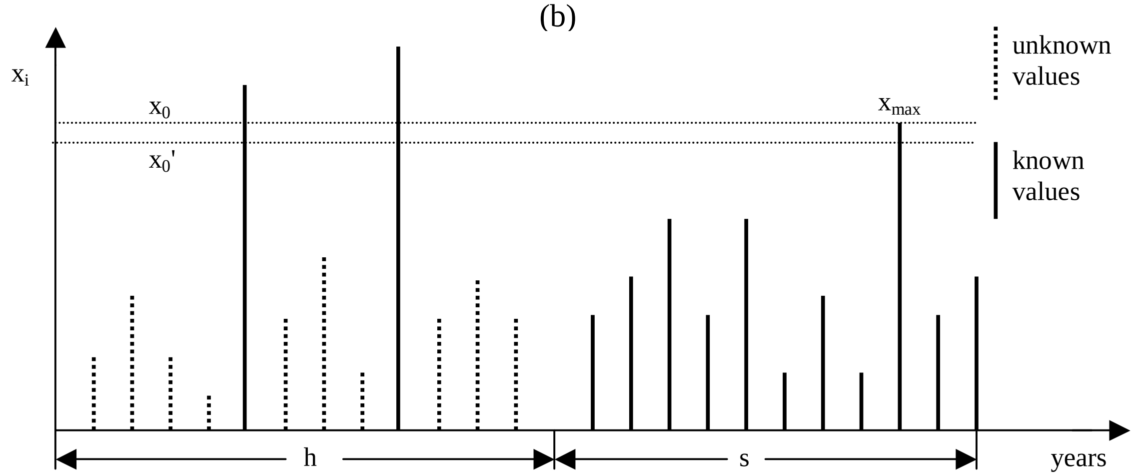
"The floods depicted [Figure 4.1] can be … interpreted as being censored below or above a threshold $x_0$. There are $h$ floods censored below $x_0$ in Figure [4.1]a and $h$-2 floods




(a)




(b)




(c)

***Figure 4.1*** *Systematic record of s years where an extraordinary flood* $x_{max}$ *has occurred, and historical record of h years with: (a) h unknown floods smaller than* $x_{max}$*, (b) h-2 unknown floods smaller than* $x_{max}$ *and 2 unknown floods larger than* $x_{max}$ *and (c) h-2 unknown floods smaller than* $x_{max}$ *and 2 known floods larger than* $x_{max}$*.*
*(After Salas et al., 1994.)*

censored below $x_0$ in Figures [4.1]b and c. However, Figure [4.1]b also indicates that two floods in the historical period have been censored above $x_0$." (Salas *et al.*, 1994)

There can be additional complications: for example, if the censoring threshold is thought to have changed during the historic period. It may be preferable to overcome these by making approximations (based on closer inspection and interpretation of the historical/paleoflood information) rather than by committing to a more complicated (and opaque) statistical analysis.

### 4.3.6 Trends

"Historical and paleological information may date from so far in the past that the frequency distribution has changed in the intervening period. In some environmental applications this can limit the utility of information about events more than 100 or 200 years in the past." (Hosking & Wallis, 1997)

Guowei and Jingping (1999) note that, in China, "There are alternating periods in which floods occur with low frequency (e.g. the 16$^{th}$ century) and with high frequency (e.g. the 17$^{th}$ century)". They also report that, for some regions, "There is a phenomenon that the extreme flood events came one by one forming a group [i.e. cluster] of extreme flood events." They ascribe these features primarily to climate variation.

Usually it is assumed that the 'flood process' is stationary, i.e. that the risk of a flood occurring is essentially the same in each year or decade. In reality, the flood behaviour of a river is determined by a web of interacting and aggregating processes: not least, those (climatic) processes which deliver extreme rainfall/snowmelt and determine the prior wetness/dryness of catchments.

"It would be difficult to prove trends from the frequency of historic marks or accounts, as the probability that a flood would be recorded will change with time." (Sutcliffe, 1987)

"Apparent trends in floods may be due to changes in the level observations, unadjusted changes in the rating curve, periods of wet and dry years, or changes of land use. It is essential to study the physical reasons for observed trends." (Sutcliffe, 1987)

"One can distinguish three periods of nearly 300 years, which were each dominated [in the Rhine catchment] by a certain weather type. Extreme weather events show great interannual variability and interdecadal variability. The wide variability of weather conditions makes it more difficult to quantify the impact of land-use change on height of floods by … time-series analysis. Therefore, for the detection and quantification of the impact of land-use change on floods in large river basins, linked hydrological and hydrodynamic models have to be applied." (Krahe, 1999)

### 4.3.7 Inadvertent bias

"There is a danger that a search for historical floods would be biased as they would be more likely to refer to lowland cities for example. Similarly, the inclusion of sites where there are records of floods before the recent record could introduce bias unless the analysis takes into account those stations where no similar flood occurred." (Sutcliffe, 1987)

"Historical streamflow information … is most easily obtained for large or densely populated drainage basins, whose frequency distributions tend to have relatively low L-CV and L-skewness. If the results are not to be biased, historical information should be developed for all sites and years back to the earliest recorded year of historical information. In practice this is rarely done …" (Hosking & Wallis, 1997)

"Statistical treatments of historic flood data that exclude description and discussion of the historical and hydrological judgements … can obscure the uncertainties in derived design flows. They have the appearance of objectivity but conceal many subjective decisions. Historical gauged flows are likely to be inaccurate and are often unknown." (Archer, 1999)

### 4.3.8 Reducing uncertainty

Cohn and Stedinger (1987) define the effective record length, *ERL*, as "the number of years of systematic data that would produce the same mean square error as a given combination of historical and systematic data." They define the average gain, *AG*, as:

$$AG = [ERL(s, h) - s] / h$$

where *ERL* is the effective record length from *s* years of systematic data and *h* is the historical record length. *AG* measures the efficiency with which the historical record is exploited to reduce the uncertainty arising from only having a relatively short systematic record.

## 4.4 ISSUES

### 4.4.1 When to consider historical or paleoflood information?

As discussed in Chapter 2, in the UK context there are often extensive sources of historical information, typically providing evidence of flood events in the last 50 to 200 years (i.e. as far back as 1800). This fits well with the typical design standard (50 to 100 years) of UK river flood defences. Given the generally colder climate of the Little Ice

Age (c. 1400-1850 with a core c. 1550-1700), there may be little incentive to research UK flood histories much earlier than about 1800, from whatever source.

Judging from experience elsewhere – especially in the US – there could be unfulfilled potential to corroborate, amplify or extend historical information by combined use of paleoflood techniques. River systems in lowland Britain have been much modified for navigation, land reclamation and agriculture. In some cases, agricultural effects have extended into upland areas. The scope for use of paleoflood techniques is likely to be greater in (relatively) undisturbed upland areas, and in making assessments of the very largest floods that a landscape has experienced (e.g. Carling & Grodek, 1994).

Unless the natural flood regime has been overridden by man's recent activity, it is advisable to consider historical flood information in any major study of flood risk. This is strongly advisable if: (i) the impact of under-design (or over-design) will be high, (ii) there is uncertainty about the rarity of a recent damaging flood, or (iii) communities adjacent to the river are palpably rich in history. Many practical flooding problems in the UK attract considerable public interest and controversy. Uncovering evidence of a locally forgotten flood can be highly effective in gaining credibility for an investigation.

It is strongly advisable to consider historical information in the assessment of structures and facilities that pose a threat to public safety in an extreme flood. Examples include impounding reservoirs and facilities handling catastrophically dangerous materials.

"Where potential hazards are extreme – as in the case of certain dams and nuclear installations – paleoflood hydrology should probably be a required part of an in-depth risk analysis." (Baker, 1987)

### 4.4.2 How many historical floods to analyse?

Hosking (1986) – see also Hosking and Wallis (1986a, 1986b) – did experimental research on cases where the historical data comprised a single observation, known to the largest flood in a given period. This choice was partly motivated by theoretical convenience and computational advantage. However, this approach underplays the potential value of historical data, and is not to be recommended.

Singling out only the largest historical flood is likely to be wasteful, unconvincing and potentially alarming. Knowledge that a flood very much higher than any in the systematic record occurred in a particular year/decade/epoch may do little more than induce terror. "We know this huge flood occurred, but we don't know whether it was a freak." On the other hand, knowledge that the largest historical flood is scarcely higher than the largest flood in the systematic record may encourage complacency about flood risk. In essence, too much weight is being placed on a single piece of information.

The largest historical floods carry the information most relevant to extreme frequency estimation, and may influence the censoring level chosen. "In order to maintain precision in estimating design floods for the Three Gorges Project, only the historical floods of 1870, 1860 and 1788 were used in the frequency analyses. The historical floods of other years were used only as collateral evidences [i.e. to corroborate rankings].” (Chen, 1993) There is inevitably a trade-off to be made between a dilute analysis of many floods, and a concentrated analysis of the largest floods.

### 4.4.3 Allocation of period represented by historical data

Hirsch (1987) highlights the importance of assigning a realistic period of record to historical information, and illustrates the bias typically introduced if the time origin is arbitrarily taken to be the date of the earliest flood marked. Unfortunately, no guidelines appear to be available.

Where the earliest historical event is supported by contemporary reporting (e.g. local newspaper, weather journal), a reasonable procedure is to search the supporting source (and any predecessor) for reports of earlier floods. If none is found, the start-date of the supporting source might be used as the time-origin of the historical flood series.

Where this procedure is not possible, a less methodical approach will be necessary. In essence, the time-origin of the series is ‘guesstimated’ from the character of the historical information. One possibility is to place the origin a fixed time (e.g. 20 years) before the first recorded event. Another possibility is to place the origin so that it precedes the first recorded event by as long a period as this (the first recorded event) precedes the second recorded event. A further possibility is to place the time-origin so that it precedes the first event by the mean recurrence interval between events in the historical record.

Examples from the 20$^{th}$ Century illustrate that memories of a large flood can be surprisingly short-lived: even in celebrated settlements (e.g. Acreman & Horrocks, 1990). This may be a product of the greater mobility of societies in recent decades. Nevertheless, in the absence of specific supporting information, it is probably unwise to ascribe a time-span longer than about 20 years to the flood-free interval terminated by the ubiquitous ‘largest flood in living memory’. In making a more daring interpretation (e.g. that the time-origin can be placed 50 rather than 20 years before the event), it will help to know the age and residence of the person who so labelled the event.

This problem – of not knowing the date from which earlier floods would have been marked had they occurred – exemplifies that analysts can rarely escape subjective decisions if they are to use historical information in a flood frequency analysis. Interpretation problems can also arise when there are gaps in the systematic record, or suspected omissions in the historic record. Resolving such problems requires hydrological understanding and an appreciation of the source (and supporting) material for the historical (or paleoflood) information. For example, where the researcher can find no explicit mention of the floods in the records available, in order to provide a good summary of the information extracted it is necessary to indicate both the period of record covered and the size of the floods that would have been recorded had such occurred.

### 4.4.4 Historical analysis *versus* pooled analysis?

When following Flood Estimation Handbook recommendations, the (conventional) preferred flood estimate will typically come from either a pooled analysis of gauged flood peak data (Robson & Reed, 1999) or an amalgam of estimates by statistical and rainfall-runoff methods (Reed & Houghton-Carr, 1999). A combined analysis of historical and systematic data from the river in question should be seen as augmenting and informing the conventional flood estimate, not displacing it.

Historical information may be available for a nearby similar catchment rather than for the river in question. In this situation, it may be reasonable to examine the influence of the historical information on the (conventional) flood estimate at the donor site, and to adjust the (conventional) flood estimate at the subject site *pro rata*. A more complicated case is if an analysis incorporating historical information can be undertaken (or already exists) for a high-ranking site in the pooling-group for the subject catchment. In this situation, it may be reasonable to adjust both the L-moment ratios and the effective record length (of the relevant station in the pooling-group) to reflect the information gain from the historical data.

### 4.4.5 Treatment of outliers

The occurrence of one or two floods very much larger than any others – so-called outliers – poses a classic dilemma.

“If the plotting position formula for such data utilises the length of systematic record … the outliers may be assigned unreasonably high probabilities. On the other hand, deletion of the outliers may lead to erroneous low probabilities for events of the outlier magnitudes.” (Baker, 1987)

“Extraordinary floods in an observed flood record are generally considered to belong to the same distribution as the other remaining observations in the sample and to contain valuable information about rare flood events which are extremely important in predicting the tail properties of a frequency curve.” (Hu, 1987)

The events are of the utmost relevance to a study of extreme flood risk, yet – with only one or two such occurrences – it is exceptionally difficult to judge their rarity. Where outliers occur in the systematic record, historical data can be invaluable in providing a longer-term perspective. But what action is to be taken if outliers are found in the historical/paleoflood data rather than the systematic record?

The FEH is scathing (Reed, 1999, pp 33-35) about analysts who dare to delete outliers from systematic records without demonstrating that the data are false. A less unbending approach may be warranted where the outliers appear in the historical/paleoflood record rather than the systematic record. Any lack of confidence in the veracity or relevance of unexpectedly large values can be reflected by reducing the weight given to the historical data when arriving at the final flood frequency estimate. In other words, it may be reasonable to downweight all the historical data, or to use only the more recent/reliable part of the historical series. But it is never reasonable to reject a particular record simply because the value exceeds expectations.

### 4.4.6 Selectivity

"The design flood of rare frequency … is usually changed considerably after the occurrence of an extraordinary flood." (Luo, 1987)

Perhaps the greatest challenge is to ensure that decisions taken are not unduly biased by occurrences. The default method will often be a conventional flood frequency estimation of gauged data. A reasonable approach may be to seek out historical data only in cases of public safety (see above), or where a flood-defence decision is sensitive (e.g. in terms of cost-effectiveness) to uncertainty in the conventional flood frequency estimate.

Where the systematic record happens to include outliers, the sample confidence intervals are likely to be wide, and a historical review will be triggered. However, where the systematic record is tame (i.e. including no large flood) the sample confidence intervals are likely to be narrow, and no historical review will be triggered. Such decisions should strictly examine confidence intervals on the frequency axis, not the magnitude axis.

An element of selectivity lurks in such an approach. The presumption is made that a data sample that includes outliers may be wild, and is likely to be distorting the flood frequency analysis. Yet no question is asked of a data sample that is freakishly tame: presumably, because there is no established index of 'domesticity'.

Pooled frequency analysis helps to reduce the sensitivity to unusual data samples. However, when dealing with larger (e.g. 100 – 10000 $km^2$) UK catchments, pooled frequency analyses can themselves be sensitive to the spatially extensive extreme events that have (or haven't) been captured in the (pooled) systematic record.

Some selectivity is unavoidable in flood frequency analysis, and may not always be undesirable. For perfectly understandable reasons, flood frequency estimates are often made for sites that have recently experienced a worryingly large flood. The issue of selectivity has been given prominence here lest – amid the complexities – the decision to undertake/omit a historical/paleoflood investigation is inadvertently prejudiced.

### 4.4.7 What about non-stationarity?

It is feasible to search for underlying trend or long-term cyclical behaviour in *average* rainfalls or river-flows, and to attempt to explain their origin. Detecting trends in *flood* series is also possible (e.g. Robson *et al.*, 1998), although considerable care is required to check that perceived effects are, in addition to being statistically significant, physically important and likely to be (chronologically) sustained. The possibility that an apparent trend may have arisen from an undetected change in rating or recording practices cannot be forgotten. Robson (1999a) illustrates – by reference to neighbouring long-record stations – how inter-decadal climatic variation can masquerade as trend in short-term flood series.

Non-stationarity in flood behaviour is difficult to prove or disprove; because the interest is in extreme values, there are relatively few data. A flood-free period of several decades may suggest a trend towards fewer floods, but provides no information about likely magnitudes when floods again occur. At the other extreme, outliers may exaggerate or conceal trends. Where outliers occur in the systematic record, historical data can be invaluable in providing a longer-term perspective. But, as discussed earlier, outliers in the historical record can be difficult to interpret.

A further difficulty is that the assumption of stationarity is pivotal to most flood frequency analysis methods, which follow the empirical approach that past flood behaviour is the best guide to present (and future) flood risk. If the combination of historical and systematic data reveals significant long-term trend, in the final analysis, flood frequency may have to be estimated from the recent systematic data alone (e.g. Archer, 1999), or from specially adjusted datasets.

Hosking and Wallis (1997, p.160) hint at a 'Catch 22' in the use of paleoflood information in flood frequency estimation, which may also apply to historical data. If the paleoflood analysis disagrees with the conventional flood frequency analysis, climate or catchment change is suspected. The assumption of stationarity is then invalid, and the data cannot be used in flood frequency estimation (see above). If, on the other hand, the paleoflood analysis agrees with the conventional flood frequency analysis, the final estimates are unchanged. The only gain is in confidence.

The above argument is stretched to make a point. In particular cases, a secure bridge may be found between the non-conventional (i.e. the paleoflood or historical information) and the conventional (i.e. the systematic data). It will be especially helpful if both types of information are available for one or more notable floods. However, where a strong bridge cannot be built, the disparate character of the systematic and historical data (or of the systematic and paleoflood data) is likely to limit the scope to draw any firm conclusion about non-stationarity.

In summary, combining historical/paleoflood data with systematic data – to estimate flood frequency – is challenge enough. It may be asking too much to infer stationarity/non-stationarity from the same information. Concern about climate or catchment-induced non-stationarity should ideally be addressed in a wider-ranging (e.g. regional) analysis that exploits additional sources of information, or by recourse to (climate and catchment) modelling.

### 4.4.8 What distribution model?

Whether or not historical data are incorporated is not especially germane to the choice of a distribution model (e.g. Gumbel, Generalised Extreme Value, Generalised Logistic, …) to summarise flood frequency. The Flood Estimation Handbook recommends use of the (3-parameter) Generalised Logistic distribution for pooled analysis of UK (annual maximum) flood series, but advocates a graphical approach when reconciling such estimates with historical flood data. When fitting a distribution by Maximum Likelihood estimation to provide a joint estimate from systematic and historical data (see below), the choice of model should not be unduly driven by computational convenience. As in pooled flood frequency analyses (Robson & Reed, 1999), a 3-parameter model is most likely to offer the right mix of flexibility and prescription.

When estimating flood frequency by a combined analysis of systematic and historical data for a specific site, Cohn and Stedinger (1987) found that the value of historical information rose considerably with each additional parameter to be estimated. This conclusion was reached by computational experiments, which sampled 50-year systematic (and 200-year censored) records from a controlled 'population'. The result does not provide a case for choosing an elaborate 4- or 5-parameter (e.g. Wakeby) distribution model when historical data are available. Rather, it reflects the imperfections of the alternative modelling strategies considered by Cohn and Stedinger. A 1- or 2-parameter model is too inflexible to do justice to 50 annual maxima and several historical flood peaks, particularly if the parent population is a 3-parameter distribution! Even for samples drawn from a known population, calibration of a 3-parameter model is imperfect, being particularly sensitive to the largest and smallest values that happen to be in the sample. This explains why they found the additional information provided by historical data to be particularly prized when fitting a 3-parameter (rather than a 1- or 2-parameter) model. We suggest that they would have reached a similar conclusion had the additional information been generated in a (simulated) pooled analysis rather than from (simulated) historical data.

Jin and Stedinger (1989) present generalised Maximum Likelihood estimators for combining historical and systematic data both in a single-site and regional (i.e. pooled) context, but present results only for the (3-parameter) GEV distribution.

### 4.4.9 Which estimation method?

Conventional flood data are well suited to application of a range of estimation methods. The Flood Estimation Handbook advocates fitting by L-moments (Hosking & Wallis, 1997), an approach that is now well established. The user can draw on a number of diagnostic tools, including L-moment ratio diagrams. These tools compensate for any theoretical inferiority of L-moment estimation to Maximum Likelihood (ML) estimation: a topic that is, in any event, contentious. The L-moment approach is also well adapted to pooled applications. Estimation by moments rather than L-moments cannot be recommended; moment estimators can be severely biased when the underlying population is skewed (e.g. Hosking & Wallis, 1997, p. 18).

The case for preferring ML estimation to L-moment estimation is stronger when considering historical flood data. This is because ML methods are well suited to handling categorical data (e.g. a censored flood peak) alongside numerical data. These situations can be handled directly by ML theory, whereas they require not-yet-available extensions to L-moment methodology. There seems to be considerable potential for applying, to L-moments, the approach used for ordinary moments in the new Expected Moments Algorithm (Cohn *et al*., 1997; England *et al*., 1998) which allows the combination of historical and systematic data. Wang (1990a, 1990b) has developed other variations on L-moment methods to accommodate censored data, but their use is less intuitive than for regular L-moment methods. Such variations have yet to be widely adopted.

ML methods have been adopted quite widely by researchers, but much less by practitioners, at least in the UK. This may reflect a perception (whether right or wrong) that ML methods are for the specialist only. However, the low take-up may be a product of the forceful recommendations (NERC, 1975; IH, 1999) to favour pooled methods.

ML techniques are well developed for single-site analysis (e.g. NERC, 1975; Clarke, 1994), and reasonably well developed for analysis of combined systematic and historical records at a site (e.g. NERC, 1975; Stedinger & Cohn, 1986). Some regional (i.e. pooled) flood frequency analyses have been developed using ML estimation, but they remain relatively specialised (e.g. Smith, 1989). Recognising the appropriateness of ML methods when analysing censored series, Jin and Stedinger (1989) present methods for pooled analysis of combined systematic and historical records. Inevitably, these are all but unintelligible to the non-specialist, because of the additional layer of complexity (and extensive options) necessarily introduced.

L-moment and graphical methods allow the user to make headway before choosing a distribution model. In contrast, ML procedures require the user to adopt a specific distribution model, so that the equations can be set up and solved.

A further discouraging feature is that the iterative schemes typically needed to reach ML solutions can fail to converge. This problem can be prevalent where a dataset includes unusual values (i.e. high or low outliers). Thus, ML procedures do not provide the user with a guaranteed result to the same extent as L-moment or graphical methods. The other main types of estimation method – besides moment, L-moment and maximum likelihood estimation – are Bayesian methods. To a certain extent these can be regarded as a modification of ML techniques but with important differences, which can help to avoid the iteration-convergence problem. However, they have the drawback of introducing extra subjectivity into an overall procedure; they are, if anything, even more computationally complex than ML procedures.

It is argued in many texts (including NERC, 1975; IH, 1999) that graphical display is essential if the user is to have confidence that a derived flood frequency model is consistent with the data. The graphical method usually adopted is a variate *versus* reduced-variate plot, showing the fitted model against the extreme-value data at the subject site (see example in Section 4.5). The argument is convincing when analysing systematic data, and unanswerable when used to compare historical data against a model based on a systematic record.

Four reasons lay behind the FEH recommendation (Reed, 1999) to adopt an informal graphical approach to incorporating historical flood data. As indicated above, a graphical display is in any event required to judge acceptability. The second reason was the lack of seasoned L-moment-based procedures for incorporating historical data. The third reason was an unwillingness to recommend complicated-to-understand ML-based methods that would inevitably have clashed with the pooled L-moment approach recommended in the FEH; more might have been attempted had the latter already been well established in UK practice. Finally, an informal graphical approach was favoured because of its inherent flexibility: noting that, in FEH practice, preferred (conventional) flood frequency estimates would themselves often be based on a combination of (conventional) methods. [The reasons have been reworded and amplified here, but are not intended to contradict those given by Reed (1999).]

There is scope to revisit this issue at some stage. This might be after experience has been gained of the different ways in which users are interpreting the FEH advice on historical development, or in response to new research findings. Meanwhile, experience needs to be gained with the extent and quality of historical information in typical UK situations. Application of graphical methods to incorporate such data will provide a good guide to how much extra information historical data can supply beyond that in the systematic record, and thus will provide an indication of the benefits of developing more formal techniques.

## 4.5 GRAPHICAL METHODS

### 4.5.1 Introduction

The character of much historical flood information is that flood $x$ is the largest in a record of $M$ years. Thus, a very natural approach is to plot the extreme values at an appropriate plotting position on a variate *versus* reduced-variate diagram, most often a Gumbel plot. This approach has been applied in many settings, and a full review would be a major undertaking in itself. Instead, the approach taken is to summarise key issues, and to comment on the options that appear most useful.

The main questions are:

- How to link the conventional and historical analyses
- How to select the historical data for plotting
- At which frequency positions to plot the historical data

- How to interpret the historical data alongside the conventional analysis
- How to adapt the flood frequency curve

Although much of the notation associated with graphical analysis of historical data is considerably older, that adopted here is the system used by Salas *et al.* (1994). Some of it has already been indicated in Figure 4.1, and the notation is confirmed in Figure 4.2.

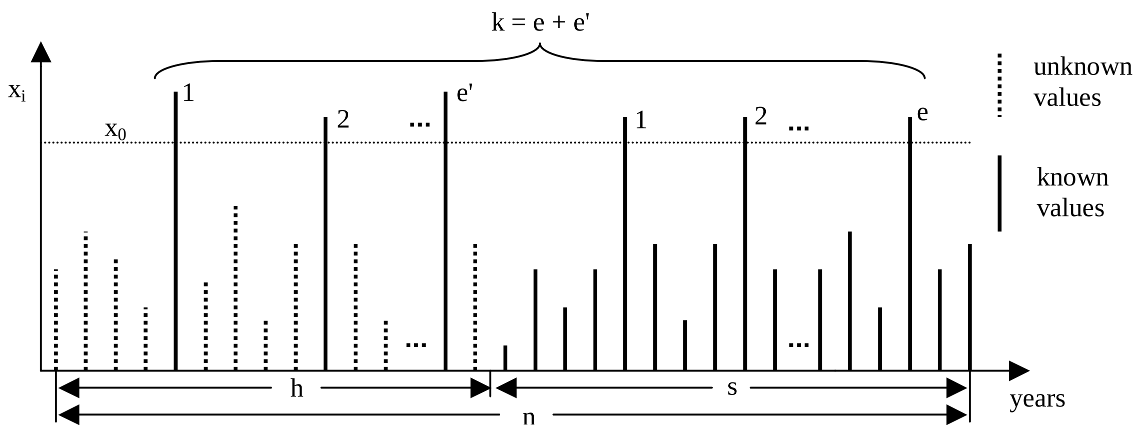



***Figure 4.2*** *Systematic and historical records with e and e' (respectively) extreme floods larger than $x_0$. (After Salas et al., 1994.)*

To the right-hand side, Figure 4.2 shows annual maximum floods for each of *s* years, *s* for systematic. To the left-hand side, a number, *e'*, of extreme floods – Salas *et al.* (1994) prefer *e* for extraordinary – are marked drawn from a period of *h* years, *h* for historical. The two periods abut: i.e. there is neither a gap nor an overlap. A threshold flood, $x_0$, is marked by a broken line across the diagram, to indicate the flow value above which extreme floods have been marked. The threshold is strictly defined by the historical record; it will often correspond to the datum above which extreme floods (within an era) have been noted. In some situations (e.g. Figure 4.1), the threshold is determined by a recent extreme flood. (It is then reasonable to set the threshold a little lower than the recent flood, as illustrated in Figure 4.1c.) The number of extreme floods in the systematic record is denoted by *e*.

This formalisation is more general than it appears. Either *e* or *e'* can be zero. Thus the approach can deal with cases where the only historical information is the period over which a recent extreme flood is thought not to have been exceeded (see Figure 4.1a).

There is no stipulation about how high or low the threshold should be drawn. However, it is usual for the threshold to be relatively high so that only the most significant historical floods directly enter the analysis. There are several reasons for this. First, there may be uncertainty about whether a lower-ranking historical flood might be missing from the flood chronology, particularly in the period prior to the first marked flood. Second, the magnitudes inferred for historical floods are usually less certain than those for recent floods, because of the limited documentation available. Third, when analysed alongside systematic records, historical flood series provide useful information even when there are no floods above the threshold. When used to augment systematic records, the principal requirement is for reliable historical information rather than lots of it.

### 4.5.2 How to link the conventional and historical analyses

It is tempting to gather all the information, carry out various analyses, and wait to see what pops out. However, because of the scope for inadvertent bias (see Section 4.3.7), a more structured approach is preferable. The approach chosen should reflect the methods available, the character of the historical information, and (perhaps) the richness of the systematic data.

In a typical case, a conventional flood frequency analysis will already have been undertaken. When following FEH recommendations (Reed, 1999), this will invariably involve a pooled frequency analysis but may also make direct use of the systematic record at the subject site. The conventional investigation may also consider a rainfall-runoff approach, either the FSR design event method (Houghton-Carr, 1999) or, as they mature, methods based on continuous simulation (Calver & Lamb, 1996).

The approach recommended here can be summarised as follows:

1. Undertake/update a detailed flood frequency analysis, with only passing reference to historical flood data, to derive a preferred (conventional) flood frequency curve;
2. Gather and evaluate the historical flood information;
3. Use a graphical approach (see below) to re-appraise the preferred flood frequency curve in the light of the historical data.

Invariably, this last step will consider all the large floods at the subject site, i.e. using both the historical and systematic data.

The investigation will inevitably be more complicated where there are important historical data at a relevant donor site rather than at the subject site itself (see suggestions in Section 4.4.4).

### 4.5.3 How to select the historical data for plotting

This topic has been discussed extensively above, and in earlier sections. Considerable care and hydrometric/hydraulic understanding are called for when converting historical flood levels to flood flows. Attention should focus mainly on the largest floods. In some basins, floodplain storage exerts a strong influence on the flood frequency relationship at the subject site. In this situation, a lower threshold may be relevant to refining the flood frequency curve in the critical sector in which conditions are in transition. However, a higher threshold would be relevant in attempts to refine the uppermost part of the flood frequency curve. In all cases, it can be helpful to classify the relative reliability of each historical flood magnitude. An advantage of a graphical approach is the ability to give more weight to some observations than to others (see Box 3.1, Section 3.4)

### 4.5.4 At which frequency positions to plot the historical data

The literature is replete with research and debate about appropriate plotting positions. Arguments in favour of one formula rather than another are supported by simulations (i.e. statistical experiments) in which flood data are drawn from an assumed 'parent' distribution model or 'population'. Hirsch (1987) and Guo (1990) assess the relative 'robustness' of different plotting position formulae to mistaken assumptions about the parent distribution: e.g. when using the plotting positions to fit a Gumbel distribution to data samples deriving from a log-normal distribution.

A plotting-position formula specifies an appropriate frequency at which to plot an ordered flood (e.g. the *i*th largest) in a series of *n* annual maximum values. The exceedance probability of $x_i$, the *i*th largest flood, is denoted by:

$$p_i = \Pr(x > x_i)$$

where Pr is read as "the probability that". Thus, $p_i$ is the probability that an annual maximum flood exceeds the given flood magnitude, $x_i$. A plotting-position formula specifies values for the $p_i$. [Warning: in many situations, the flood peaks are ranked in ascending order rather than descending order. In such cases, the plotting position, $p_i$ denotes a non-exceedance probability.]

Various plotting-position formulae have been suggested in the literature. The most popular ones are special cases of the more general formula introduced by Cunnane (1978):

$$p_i = \frac{i - \alpha}{n + 1 - 2\alpha}, \quad i = 1, \ldots, n \qquad [4.1]$$

$\alpha$ is a generalising constant; a value of $\alpha = 0.44$ yields the Gringorten plotting-position formula. The Gringorten formula is approximately quantile-unbiased (i.e. performs well when estimating flood magnitudes of a given frequency) for samples drawn from a Gumbel distribution (NERC, 1975).

In UK practice, the convention is to plot the flood peak (in $m^3s^{-1}$) on the vertical axis and the frequency on the horizontal axis, in a so-called variate *versus* reduced-variate plot. The reduced-variate scale transforms frequency to a linear axis. Until publication of the FEH, the convention was to adopt the Gumbel reduced-variate:

$$y = -\ln(-\ln(1 - p_i)) \qquad [4.2]$$

The FEH favours use of the Logistic reduced-variate:

$$y = -\ln(\, p_i \ \ / \ \ (1 - p_i)) \qquad [4.3]$$

[Note that the FEH is one instance where $p_i$ is used to denote the non-exceedance probability: this is the reason for the formulae here being apparently different from those in the FEH].

The particular choice of reduced-variate scale affects the look of the extreme-value plots, and will consequently influence visual assessments. However, the choice is not especially relevant to the discussion of historical *versus* conventional treatments presented here.

When incorporating historical data in the format of Figure 4.2, Hirsch (1987), Hirsch and Stedinger (1987) and Salas *et al.* (1994) favour use of the plotting-position formulae:

$$p_i = \frac{i-\alpha}{k+1-2\alpha}\,\frac{k}{n}, \ \ i = 1,\ldots,k \qquad [4.4a]$$

$$p_i = \frac{k}{n} + \frac{n-k}{n}\,\frac{i-k-\alpha}{s-e+1-2\alpha}, \ \ i = k+1,\ldots,k+s-e \qquad [4.4b]$$

where $\alpha$ denotes the plotting-position constant introduced by Cunnane (1978). A common choice in UK practice is $\alpha = 0.44$, consistent with use of the Gringorten formula for plotting systematic data. Here, $n$ is the combined record-length (in years) of the historical and systematic data, i.e. $n = h + s$. Note that $k$ denotes the total number of extreme floods (i.e. the number of floods exceeding the threshold flow value of $x_0$) in the combined period, i.e. $k = e + e'$.

It should be noted that Equations 4.4 provide a system for plotting historical and systematic data jointly on the same diagram. The diagram relates flood magnitude, $x$, to annual non-exceedance probability, $p$. Equation 4.4a applies to all the floods that lie above the extreme-flood threshold. In other words, it applies both to the floods in the historical flood series and to those floods in the systematic record that lie above the threshold defining the historical flood series. Equation 4.4b applies to all the other floods, i.e. to the floods in the systematic record that fall below this threshold.

We broadly support use of Equations 4.4 in appropriate circumstances, principally when historical and systematic records for a particular site are being plotted for comparison with a preferred flood frequency estimate derived without reference to historical data. But see the recommendations later. In many cases, the user may choose only to plot the floods that rise above the threshold, i.e. applying Equation 4.4a but not Equation 4.4b. For completeness, the basis of each equation is now explained.

**Explanation of Equation 4.4a**

Equation 4.4a specifies plotting positions for the $k$ largest floods, i.e. those larger than the threshold $x_0$. If these $k$ floods were drawn from just $k$ years, the usual plotting-position formula (Equation 4.1) would apply, with $k$ replacing $n$. In fact, the $k$ floods are drawn from $n$ rather than $k$ years, the remaining $n$-$k$ years having annual maxima below the threshold.

The plotting position for $x_i$ specifies the exceedance probability of $x_i$, i.e. $\Pr(x>x_i)$, the annual exceedance probability. We know that, for $x$ to represent an extreme flood (i.e. the case dealt with by Equation 4.4a), the flood comes from a year in which a flood greater than $x_0$ occurs. However, we want a flood that comes from such a year and exceeds the particular flood value (or "quantile") of interest, $x_i$. Thus, we require $x>x_0$ and $\langle x > x_i \,|\, x > x_0 \rangle$. The vertical bar is read as "given that".

The required probability is thus, for $x_i>x_0$

$$\Pr(x > x_i) = \Pr(x > x_0)\Pr\langle x > x_i \,|\, x > x_0 \rangle \qquad [4.5]$$

The probabilities $\Pr(x > x_0)$ and $\Pr\langle x > x_i \,|\, x > x_0 \rangle$ are multiplied because *both* of the conditions have to be satisfied. The probability $\Pr\langle x > x_i \,|\, x > x_0 \rangle$ is read as "the probability that $x$ exceeds $x_i$ given that $x$ is known to exceed $x_0$".

Now, the probability that a year drawn at random has a flood greater than the threshold can be simply estimated as $k/n$, since $k$ of the $n$ years in the data sample provide such a flood. Thus:

$$\Pr(x > x_0) = \frac{k}{n} \qquad [4.6]$$

As indicated in the first paragraph of this explanation, the other probability is obtained by replacing $n$ with $k$ in Equation 4.1, i.e.

$$\Pr\langle x > x_i \,|\, x > x_0 \rangle = \frac{i - \alpha}{k + 1 - 2\alpha} \qquad [4.7]$$

inserting Equations 4.6 and 4.7 into Equation 4.5 yields the required relationship Equation 4.4a.

**Explanation of Equation 4.4b**

The logic behind Equation 4.4b is summarised in less detail than for Equation 4.4a. Equation 4.4b applies to floods falling below the threshold magnitude $x_0$.

The quantile $x_i$ will be exceeded if *either*: (i) the year has a flood greater than $x_0$, *or* (ii) the year has a flood less than $x_0$ *and* $x$ is greater than $x_i$. This argument leads to the probability statement for $x_i < x_0$:

$$\Pr(x > x_i) = \Pr(x > x_0) + \Pr(x \le x_0)\Pr\langle x > x_i \mid x \le x_0 \rangle \qquad [4.8]$$

Note that the probabilities of the two states are added because either condition will lead to $x$ being greater than $x_i$ and they are mutually exclusive.

The probability of the first state is given (as previously) by Equation 4.6. Turning to the second state, the probability that a year drawn at random – from any part of the record – has a maximum flood that does not exceed the threshold can be estimated as $(n\text{-}k)/n$, i.e.

$$\Pr(x \le x_0) = \frac{n-k}{n} \qquad [4.9]$$

This equation is complementary to Equation 4.6. The probabilities in Equations 4.6 and 4.9 must of necessity add up to 1.

The remainder of the derivation of Equation 4.4b mirrors the derivation for Equation 4.4a. There are $s$-$e$ floods in the dataset that do not exceed the threshold: the $s$ floods in the systematic record less the $e$ floods that are extreme. Thus, the probability of the second state in Equation 4.8 can be obtained by substituting $s$-$e$ for $n$ in Equation 4.1, and by applying Equation 4.9. This leads to the required:

$$p_i = \frac{k}{n} + \frac{n-k}{n}\,\frac{i-k-\alpha}{s-e+1-2\alpha},\ i = k+1,\ldots,k+s-e \qquad [4.4b]$$

Hirsch and Stedinger (1987) provide formal justifications for using Equations 4.6 and 4.9.

**Recommendations for plotting historical data**

The Flood Estimation Handbook recommends that the largest floods from the combined historical and systematic record are plotted using the Gringorten formula (i.e. Equation 4.1 for $i$ = 1,…,$k$ with $\alpha$ = 0.44). This differs from the suggestion to use Equation 4.4a with $\alpha$ = 0.44, although the differences are typically very small. The differences are large enough to be noticeable only when $k$ is very small in comparison to $n$, e.g. if the threshold is set so high that only the very highest floods per century are plotted.

The advantage of using Equations 4.4 is that they allow the systematic data below the threshold to be plotted in a consistent fashion that is compatible with the other gauged data (i.e. the historical floods and the systematic data that exceed the threshold). However, an undesirable feature of Equation 4.4a is that the plotting positions of the very largest floods are dependent on the threshold, $x_0$, chosen to define them. This is because the plotting positions involve $k$, rather than just $i$ and $n$.

It is counterintuitive for the frequencies assigned to these floods to vary in this manner. The effects are very minor and are unlikely to be noticed where the procedures are applied by software. The undesirable feature could be eliminated by choosing $\alpha = 0.5$ (rather than $\alpha = 0.44$), since Equation 4.4a then degenerates to the visual form of Equation 4.1. Such a choice – corresponding to the Hazen formula – would, however, be controversial in other respects.

Thus, the recommendation is to apply Equations 4.4 (with $\alpha = 0.44$) in cases where the threshold defining the historical flood series provides ample extreme floods to plot (e.g. more than five per century).

### 4.5.5 How to interpret the historical data alongside the conventional analysis

An informal approach is recommended for assessing what the historical data indicate about the flood frequency curve derived by a conventional analysis.

In addition to plotting the largest floods (from the historical and systematic records) according to Equation 4.4a, various embellishments are possible. Different symbols can be used to indicate the degree of confidence with which the magnitudes of particular floods are known (see example in Section 3.4). Alternatively, a narrow vertical bar (or 'whisker') may be added around the historical points to indicate the range within which the flood magnitude is thought to lie.

It is more complicated to present a visual indication of uncertainty in the probabilities (frequencies) assigned to each historical event, since a missing flood corrupts the rankings of smaller floods in the historical record.

Where the historical record includes a flood of *intervening* rarity but unknown magnitude, it may be advisable to adopt a very coarse estimate of the magnitude, and to proceed with the graphical assessment (the degree of coarseness can be reflected by a suitable embellishment on the plot). The alternative would be to adopt a plotting or analysis scheme that is so complicated or obscure as to be inexplicable (and therefore unconvincing) to the non-specialist.

Where the magnitudes of the largest floods are highly uncertain, others might recommend a formal analysis of the flood series as a binomially-censored series (see Section 4.3). However, under the informal graphical approach recommended here, the uncertainty attached to the magnitudes of the largest floods can be made clear in the symbolisation. The eye can then be drawn to what the historical series as a whole says about the frequency with which some lower flood threshold is exceeded, which is all that a formal binomial-censored analysis would provide.

### 4.5.6 How to adapt the flood frequency curve

There are several possibilities. If the plot shows reasonable accord between the historical data and the flood frequency curve preferred in conventional analysis, the latter is retained with increased confidence.

If the historical data suggests that the preferred flood frequency curve may be overestimating flood magnitudes, considerable caution is required before adapting the flood frequency curve. A thorough test of the authenticity, completeness and accuracy of the historical data needs to be made before lowering the flood frequency curve. Caution is required because of the possibility that some historical floods may not have been noted or that the historical flood information is in some way not representative of the current flood regime.

Checks are also advisable if the historical data suggest that the preferred flood frequency curve may be underestimating flood magnitudes, to check for any mistaken logic or inadvertent bias in assembling the historical flood series. If no error or bias is found, the preferred flood frequency curve should be adjusted to gain better agreement with the historical data points.

Possible strategies for making such an adaptation include, in the case of a preferred flood frequency curve coming from a pooled analysis:

- To change the distribution model used to represent the flood growth curve (e.g. swapping from Generalised Logistic to Generalised Extreme Value);
- To arbitrarily adjust the estimate of the index flood, sacrificing good agreement of QMED with the systematic data in favour of improved agreement between the historical data and the upper reaches of the flood frequency curve;
- To review the pooling-group (and weightings) used in deriving the pooled flood growth curve, perhaps reducing the number of stations used and changing the weightings to further reflect the gauged catchments thought to be most similar to the subject catchment;
- To derive (by trial and error) a flood frequency distribution (of the preferred model) which provides a good visual fit to the systematic and historical data at the subject site, and then to adopt intermediate values of the (pooled and single-site) L-moment ratios, to derive a new set of model parameters which yield an intermediate flood growth curve.

If the preferred flood frequency curve comes from a rainfall-runoff method – or a hybrid (statistical and rainfall-runoff) method – it may be reasonable to adapt a key parameter of the rainfall-runoff model, such as the standard percentage runoff.

Alternatively or additionally, the preferred flood frequency curve can be adjusted manually, to gain better agreement (in the plot) with the historical flood data.

## 4.6 SUMMARY OF GUIDANCE

A combined analysis of historical and systematic data from the river in question should be seen as augmenting and informing the conventional flood estimate, not displacing it.

Historical investigations should be a required part of in-depth risk analysis where river flooding poses a critical threat to the safety of sensitive installations.

There has been relatively little use of paleoflood techniques in extreme flood estimation in the UK. Greater consideration should be given to their use, in locations favourable to the recovery of paleoflood data.

Historical searches are to be encouraged in all major investigations. Though useful as a pointer to unusual events, and as a general prompt, the BHS Chronology of British Hydrological Events (www.dundee.ac.uk/geography/cbhe) should not be seen as the only source of historical flood information (see Chapter 2). The collection is, as yet, patchy, since inevitably it comprises information on those rivers of interest to the principal contributors. A useful enhancement to the database would a pointer to indicate newly recovered/interpreted data.

The desired acceptance of the technique as an integral part of major flood investigations could be held back if historical series are insufficiently researched, or if too much weight is attached to unsupported anecdotal information.

Hydrological experience is crucial if inferences from historical information are to be credible. While general, the need for experience is especially obvious in river systems that are occasionally liable to unusual types of flooding, e.g. ice-jams (Wijbenga *et al.*, 1994), debris dams (Hewitt, 1982), or fluvial-tidal interaction.

Interpreting historical records requires hydrological understanding, and an appreciation of the source of the historical information. Where there is doubt, supporting (i.e. collateral) material should be sought.

Statistical care is needed, especially when using unfamiliar or specialised procedures such as maximum likelihood estimation.

Because of the range of skills required, historical flood investigations may benefit from teamwork and cross-checking.

A graphical approach is valuable in illustrating, interpreting and reconciling historical flood data with a flood frequency curve derived by conventional methods. Imaginative use of symbols can help to distinguish the different origin/quality/uncertainty of individual historical flood peaks.

As in all flood frequency investigations, adequate records should be kept to allow audit. Documentation is crucial if historical flood investigations are to retain credibility. Items to be recorded include:

- the methods used to research the flood history of a particular river;
- the historical data recovered;
- the methods/models used to convert water-level information to flow estimates;
- the preferred flood frequency curve prior to use of the historical data;
- the manner in which the historical flood data informed or modified the final choice of flood frequency curve.

# 5 The River Avon at Evesham Worcestershire: a case study

## 5.1 INTRODUCTION

During Easter 1998 the Avon Valley experienced severe flooding. The Stratford-Upon-Avon Herald described the event as the 'flood of the century' and at Evesham the gauging authority quickly realised that it had exceeded any other since formal gauging began in 1937. But just how exceptional was the 1998 event at Evesham?

Despite a relatively long gauged record (more than 60 years to date), the collation of historical flood information for the Avon at Evesham is likely to assist in the assessment of the severity of the flood. The compilation of flood data that pre-date the formally gauged record will enable the 1998 flood to be placed in historical context and the incorporation of this information into flood frequency analysis for this site may lead to better estimates.

The location, assimilation and evaluation of historical flood information for the Avon at Evesham serves to illustrate the guidance given in Chapters 2 and 3. The incorporation of this information into the flood frequency analysis for this site (Section 5.7) also provides an example of the graphical procedures described in Chapter 4.

## 5.2 THE AVON CATCHMENT TO EVESHAM

### 5.2.1 Catchment description

From its source near Naseby in Northamptonshire, the Warwickshire Avon flows in a south-westerly direction to its confluence with the River Severn at Tewkesbury. The catchment area to Evesham is 2200 $km^2$ and is dominated by agricultural land use, but does include the city of Coventry and the towns of Rugby, Redditch, Leamington Spa, Warwick and Stratford-Upon-Avon (Figure 5.1).

Catchment descriptors published in Volume 5 of the Flood Estimation Handbook (Bayliss, 1999b) indicate that with an $URBEXT_{1990}$ value of 0.042 the catchment can be categorised as 'slightly urbanised'. Precipitation is generally moderate with an average annual rainfall of 654 mm (based on the standard period 1961-90). Catchment geology and soils are relatively impermeable and the catchment responds quickly to heavy rainfall when soils are wet. The standard percentage runoff estimated using the Hydrology of Soil Types (HOST) classification (see Boorman *et al*., 1995) is 43.1%, reflecting the responsive nature of the catchment. The combined effect of all lakes and reservoirs, large enough to be represented on an OS 1:50000 map, is estimated as 0.977 (see Section 5.2.2) by the Flood Attenuation from Reservoirs and Lakes (FARL) index described by Scarrott *et al*. (1999).

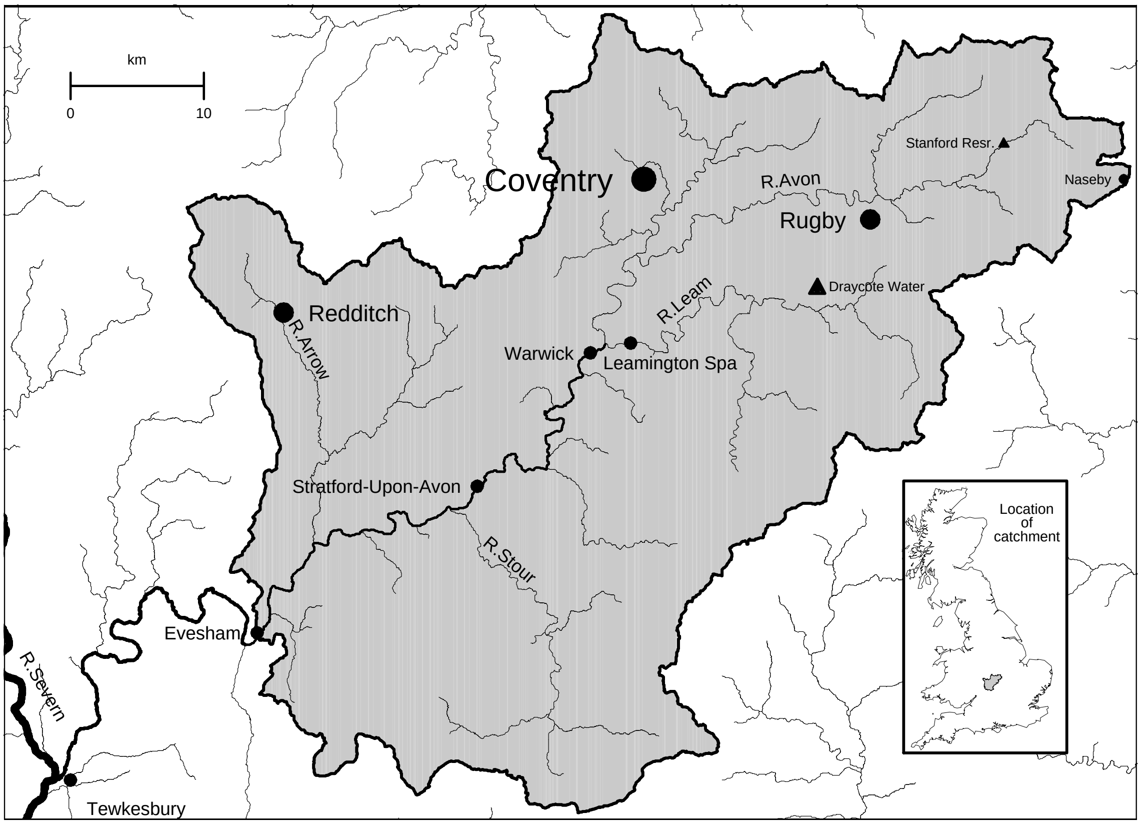



***Figure 5.1*** *The Avon catchment to Evesham*

### 5.2.2 Impact of man-made changes

Man-made changes that may have resulted in changing the flood regime through recent historical time are likely to be numerous but include: increasing urbanisation, reservoir construction and the confinement of the river by flood banks and walls.

The effect of expanding urbanisation is likely to be one of increasing both the frequency and magnitude of floods. However, more recent developments often include artificially created 'balancing ponds' or flood storage areas to temper this effect. For example, there are numerous on-line and off-line storage areas in the upper reaches of a major tributary (River Arrow) to negate the increase in runoff produced by Redditch New Town (NRA, 1994).

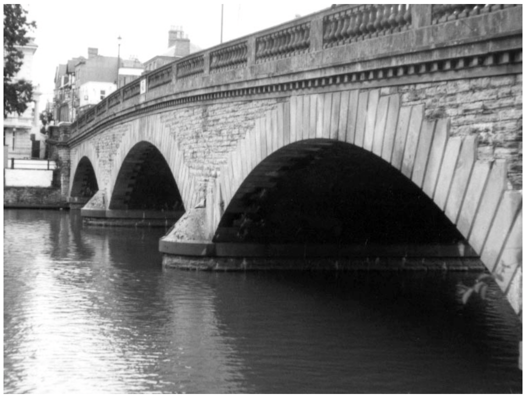
The Register of British Dams (BRE, 1994) lists details for 28 dams built in the catchment to Evesham, the majority of which relate to relatively small impoundments. The principal reservoirs in the catchment are at Stanford-on-Avon and Draycote near Rugby. The former was built in 1928 for public water supply and the latter constructed more recently (1969) as a pumped storage reservoir to take water from a major tributary, the River Leam. The FARL value of 0.977 (see above) indicates that some attenuation of floods occurring at Evesham may take place but the overall effect is unlikely to be significant.

Flood plains provide natural storage areas at times of flood and are important in providing relief for those downstream. A feature of developing flood plains for residential and commercial purposes, and protecting them with walls and embankments, is to remove these natural storage areas. Flood plain development in the lower and middle Avon however, is largely limited to unprotected caravan parks. In 1994 there were 13 flood alleviation schemes in the Avon catchment as a whole, protecting around 250 hectares of land (NRA, 1994). The impact of protecting this relatively small area of land, when compared with the total available for flood plain storage, is therefore likely to be small.

Increasing urbanisation, construction of reservoirs, loss of flood plain storage and other factors such as the intensification of agriculture, may all be influential in changing the way a catchment responds. What then are the likely impacts of man-made changes to the catchment on the flood regime at Evesham? Quantifying the impact of these factors is inherently difficult. Undoubtedly major settlements within the catchment expanded considerably during the latter part of the 20th century but land use is still predominantly agricultural and the construction of reservoirs and artificial storage areas may in some cases balance the effects of increasing urbanisation. It is believed therefore that the effects of changes in land use on this catchment in recent historical times are relatively small and likely to diminish still further when analysing floods of historic proportions.

## 5.3 RIVER FLOW GAUGING

An autographic water level recorder was established by the River Severn Catchment Board on the right bank of the Avon, just upstream of Bengeworth or Workman Bridge in September 1937 (Figure 5.2). The site benefits from the river channel being confined between well-defined masonry walls, but the choice of site was also influenced by the recording of flood levels on a gauge board on the opposite bank by Messrs. Burlingham & Co. (a builder's merchant) since 1st October 1848. Gauging is carried out 1 km down river on the downstream side of Abbey Bridge, where measurements can be made both in the main channel by cableway and on the floodplain from the bridge approaches. The station is well rated by current meter to above bankfull stage. Extrapolation of this stage-discharge relation can be based on estimates of severe events, such as the July 1968 flood, computed using a velocity-area estimate of the main channel flow combined with a Manning equation method estimate of the flood plain flow. The control for the reach is Chadbury weir, just over 4 km downstream from Abbey Bridge.



*Bengeworth or Workman Bridge*

Abbey Bridge was built as recently as 1928, but there was mention of a bridge between Bengeworth and Evesham as early as 1159. The bridge was "dreadfully injured" by a flood in 1374, but suffered its severest damage in 1644 at the hands of Royalist troops. It was repaired 18 years later and served the communities well until 1843, by which time it had become dangerous. It was replaced in 1856 by the current bridge, named after the Mayor of the time, Mr. Henry Workman.

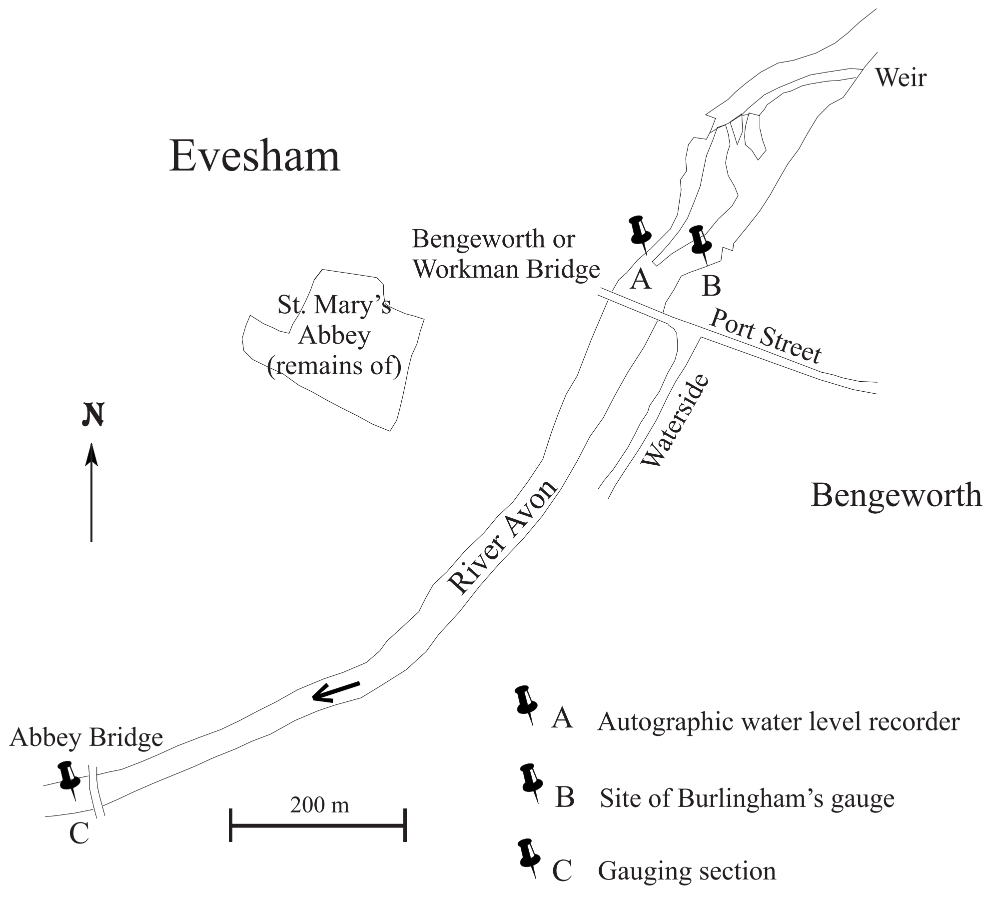



***Figure 5.2*** *The Avon at Evesham – showing location of present-day recorder (A), historic gauge board (B) and gauging section (C).*

## 5.4 HISTORICAL FLOOD CHRONOLOGY FOR EVESHAM

The ancient market town of Evesham can be traced back to the eighth century when St. Egwin, the third Bishop of Worcester, was responsible for the building of an abbey on the spot where the Virgin Mary was believed to have appeared before a humble swineherd called Eoves. The area became known as Eoveshomme, and later as Evesham. The town grew around the Abbey, which was reputed to be the third largest and most powerful Abbey in England when it was surrendered to Henry VIII in 1539.

### 5.4.1 The early flood record

In many areas of the country, there is a paucity of contemporary information on floods that occurred before the establishment of local newspapers. In the Evesham area local events were not widely reported until the middle of the 19th Century, but reference to an early flood was made by local historian William Tindal (1794) in his book 'History of Evesham'. "*We find mention of a bridge here* [Bengeworth, Evesham] *as early as the year 1159. It must however have undergone many partial, if not total repairs, as again, in the year 1374, we find the greater part of it swept away by fflood"*. Early references to floods are often made in the context of describing damage to bridges and some fifty years later May (1845) notes that an entry in a conventual chronicle records *"that in 1374 this bridge* [across the Avon at Bengeworth] *was dreadfully injured by a flood"*, confirming the severity of the 1374 flood.

Floods noted at other towns along the Avon and tributaries, may provide clues to events that may have occurred at Evesham. An account in the parish register for Welford-on-Avon reproduced by Savage (1929) and Walls (1935) describes a most extraordinary flood on 18th July 1588 that washed away both ends of Clopton Bridge at Stratford-Upon-Avon. However, the 30th July 1875 edition of the Stratford-Upon-Avon Herald, contains an article, which, in its discussion of historic floods on the river, refers to a remarkable flood on the River Avon, described in Tewkesbury town records, that is stated to have occurred on the 19th July 1587 (see also Appendix C). The article goes on to cast doubt over the authenticity of the date recorded in the parish register and speculates that the descriptions refer to the same flood event and that it occurred in 1587. In any case, it is evident that a notable flood occurred on the River Avon either in the 1587 or 1588 but, tantalisingly, its occurrence at Evesham remains, as yet, unconfirmed.

In a diary of events to the early 1800s, May (1845) again provides detail of a historic flood that inundated streets and houses in Bengeworth. *"1770 – In November of this year, the highest flood within memory occurred here* [Bengeworth]. *The water reached almost to the key-stone of the main arch of the bridge, and extended up Port-street to the public pump on the south side of the street. So that the inhabitants were compelled to pass put of their houses, through the upper windows, and were thence conveyed by boats along the street."* George Symons (1876) in a paper to the Institution of Civil Engineers refers to the 1770 flood at Evesham, when attempting to put the floods of 1875 in historical context. His description is almost identical to that given above but he goes on to estimate the peak level as *"probably 15 ft 0 in. above ordinary level"*.

Collections of photographs of historical interest published in book form have become increasingly popular. In addition to the images themselves, the captions that accompany photographs of rivers or floods can, in many cases, provide valuable information. A compilation of picture postcards for Evesham (Baylis, 1985) includes a scene of Port Street in flood in 1900. This particular flood is well documented elsewhere but the caption usefully gives details of other historic floods that affected the residents of Bengeworth. The author quotes directly from the diary of the Reverend Thomas Beale, Vicar of Bengeworth. His entry for the 10th February 1793 noted *"a most extraordinary flood within about 14 inches as high as that of November 1770 and more injurious. It was in ye parlour of ye Unicorn and Mr Stickley's oven"*. The late 1700s appears to be a relatively flood-rich period because the same caption provides information on a flood of similar proportions some six years later. On this occasion the quote is taken directly from a local attorney's memorandum book for 1799. His entry for the 6th November reads *"Flood rose in one night to the Unicorn in Bengeworth. Mr Lunn drowned"*.

Newspapers reporting on events for Evesham and the surrounding area were not well established until the middle of the 19th Century. However, descriptions of flood events in local newspapers produced from this time sometimes included a retrospective look at other historic floods (for example, the discussion of the 1587, or 1588 flood, in the Stratford-Upon-Avon Herald of 30th July 1875). In a similar vein, The Evesham Standard & West Midland Observer of 5th January 1901, in an article that talks of great floods that have affected the town, hints that a notable flood occurred at Evesham in the early 1800s by stating that *"Possibly a flood at the beginning of the century was greater than that* [1848 flood] *…"*. At that time many saw the 1st January 1901 as the dawn of the 20th century rather than the 1st January 1900. The flood that had just occurred (i.e. on 31st December 1900) had already been described at considerable length in the report, so the period referred to is most likely to be the early 19th century. Another local newspaper, the Evesham Journal, carried a report on 5th January 1901 that speaks of the flood of 1801. *"From the traditions handed down by old inhabitants there is no doubt that the present flood* [1900] *is higher than that of 1801"*. Neither newspaper reports gives details. Symons (1876) refers to a flood that occurred at Stratford-Upon-Avon in 1801, but frustratingly does not list such an event at Evesham (see Appendix A).

A search of quotations on the British Hydrological Society's 'Chronology of British Hydrological Events' (see Section 2.6), relating to rivers within the Severn basin, revealed information taken from the Warwickshire Advertiser of 4th Feb 1809 that describes a notable flood that occurred a few days earlier. *"The Avon rose to a considerable height during the late rapid thaw. The river rose so high between Evesham and Worcester as to put a stop to all communications between the two places by the normal road. A warehouse at Evesham was washed down. The bridge at Ecklington* [Eckington] *was partially destroyed and Pershore Bridge is considerably injured"*. The reference to Worcester is confusing, but relates only to the road between the city and Evesham, since Worcester lies on the Severn, some distance upstream of the confluence with the Avon at Tewkesbury. Although the event on the Avon appears to be unconfirmed elsewhere, an exceptional flood resulting from rain melting deep snow did occur in late January 1809 on the Thames (Symons & Chatterton, 1895), a river with which the Avon shares a watershed through the Cotswold Hills.

Christmas Day 1821 saw another notable event recorded on a flood board upstream at a Stratford-Upon-Avon flourmill, owned by Messrs C. Lucy and Nephew. Their flood record for the mill, reproduced by Symons (1876), gives the peak level as 5 ft 8.25 in. above the weir. This event remains unconfirmed at Evesham but Potter (1978) includes December 1821 in his list of 'benchmark' events with the annotation "Floods in the Midlands". Symons also reports on an event at Evesham that occurred on June 26th 1830. *"Violent thunderstorm; the river during the night rose from its usual level to about 14 ft 0 in"*. Conversely, on this occasion, no event was reported upstream at Stratford-Upon-Avon (see Appendix A).

### 5.4.2 Flood levels 1848 – 1937

From 1st October 1848, to the installation of an autographic recorder by the River Severn Catchment Board in 1937, the primary source of flood peak records for the Avon at Evesham is the flood levels recorded by Messrs. Burlingham & Co. at a site just upstream of Bengeworth Bridge (Figure 5.2). The gauge board was not read daily, but all major floods are thought to have been recorded over a period of 89 years (over 80 floods in all).

In the early 1970s the Severn River Authority (SRA) took the level record observed by Burlingham, carefully reduced these levels relative to Newlyn datum, and produced a subset of 55 events which exceeded a threshold level of 73 m AOD (see Appendix B). Although these data can be seen as the definitive flood level record for this period, alternative levels for some of the events listed in this subset, and additional events not given, have been documented elsewhere.

Firstly, there is George Symons's paper on the floods in England and Wales during 1875. He gives details on a number of events that occurred during the 19th Century, both at Evesham and upstream at Stratford-Upon-Avon (reproduced *verbatim* in Appendix A). Secondly, Southall (1895) in a paper to the Royal Meteorological Society following the floods of November 1894, gives flood levels for five events at Evesham that occurred between 1848 and 1875 (Appendix C). Thirdly, the Evesham Journal of 12th January 1901, as part of its coverage of the 'new century flood', lists flood levels from 1848 to the great flood of 31 December 1900 that prompted the review. These levels (see Appendix D) are undoubtedly taken from Burlingham's record but do include events not given in the SRA list. Finally, in much more recent times, following the floods of Easter 1998, the Evesham Journal (16th April 1998) listed peak levels for the previous 'top ten' floods from 1st October 1848 (Appendix E). Again, these appear to be largely based on Burlingham's record.

### 5.4.3 Flood levels and flows 1937 – 1969

When the Severn River Authority produced the list of 55 flood levels taken from Burlingham's record in the 1970s, they brought the dataset up to date by adding flood levels taken from the autographic recorder (Section 5.3). This included peak flows ($ft^3s^{-1}$) for all events except that of 20$^{th}$ October 1939. The period 1937-1969 represents the early part of the formally gauged record at Evesham, and would not normally be described as a part of the historical flood chronology. However, since the SRA has combined flood levels taken from Burlingham's record with the early autographic record and have reduced the levels to the same datum, it is convenient to present the list (Appendix B) in its entirety.

## 5.5 EVALUATION OF HISTORICAL FLOOD DATA

The evaluation of historical flood data can be messy. The process has been "likened to solving a jigsaw for which an unknown number of pieces are missing, others are damaged, and some belong to a different puzzle" (Reed, 1999). It is essential that a rigorous appraisal of all the historical information collated is undertaken, to gain maximum benefit from the assembled data.

It is evident that the historical flood chronology for the Avon at Evesham (Section 5.4) comprises information of varying quality and completeness. It is also clear that details regarding some historic flood events at Evesham are available from a number of sources. In order that this information be appraised in a systematic way it is necessary that all data are brought together to facilitate cross-referencing between the datasets provided by these different sources. A spreadsheet is a simple but effective way to hold such information. Appendix F presents the spreadsheet of all flood data (1374 – 1969) that were collated for Evesham. Table 5.1 provides an extract from that spreadsheet for historic flood events between 1374-1848. Columns A to E present peak levels taken from the primary data sources relevant to each historic flood (see Appendices A to E for further details).

### 5.5.1 Use of a tick-box procedure

Sections 3.3 and 3.4 describe how a tick-box procedure can be used to evaluate historical flood information in terms of completeness and authenticity. This procedure has been applied to 87 historic flood events thought to have occurred between 1374-1937 on the Avon at Evesham. The record 1937-1969 is taken from the early part of the formally gauged record (Section 5.3) and is not included in the tick-box evaluation presented in Appendix G. The appraisal of information for a sample of those historic floods, using a tick-box approach, is given in Table 5.2, along with notes made during the evaluation. Each historic flood is assigned a reference number to facilitate cross-referencing between the spreadsheet (Table 5.1), and the evaluation notes and tick boxes (Table 5.2).

| Ref. | Year | Month | Day | A | $B_1$ | $B_2$ | C | D | E | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 1374 | | | | | | | | | Tindal (1794) and May (1845) both refer to a flood in 1374 that damaged a bridge between Bengeworth and Evesham. |
| **2** | 1587 | Jul | 19 | | | | | | | Savage (1929) and Walls (1935) both reproduce an extract from the parish register for Welford-on-Avon which describes a flood on 18 July 1588 which damaged Clopton Bridge at Stratford-Upon-Avon. The date of the event is thought to be incorrectly recorded, and is the 19 July 1587 event noted in Tewkesbury town records (see Appendix C). The severity of the flood indicates that it is extremely likely that a notable event occurred at Evesham. |
| **3** | 1770 | Nov | 17 | 15.00 | | | | | | Symons (1876) records the 1770 flood as 'The highest flood within memory…probably 15 ft 0 ins', some 3 ins above the 1848 flood. |
| **4** | 1793 | Feb | 10 | | | | | | | Baylis (1985) quotes from the diary of the Vicar of Bengeworth which describes a flood that was said to be within 14 inches of the 1770 flood. |
| **5** | 1799 | Nov | 6 | | | | | | | A local attorney's memorandum book for 1799 describes a flood that reached the Unicorn Inn, Port Street, Bengeworth (Baylis, 1985). |
| **6** | 1801 | | | | | | | | | At Stratford both Symons (1876) and the Stratford-Upon-Avon Herald (29 Mar 1867) state that the 1801 flood was higher than that of 1848. The Evesham Standard & West Midland Observer (5 Jan 1901) reports that a flood in the early 1800s [likely to have been that of 1801] was possibly bigger than that of 1848. The Evesham Journal (5 Jan 1901) reports that “there is no doubt that the present flood [31 Dec 1900] flood was higher than that of 1801”. Thus, the 1801 flood is ranked higher than that of 1848 but lower than that of 1900. |
| **7** | 1809 | Feb | | | | | | | | The BHS 'Chronology of British Hydrological Events' provides a quotation taken from the Warwickshire Advertiser of 4 Feb 1809 that describes a notable flood that caused damage to bridges along the Avon and a warehouse at Evesham. |
| **8** | 1821 | Dec | 25 | | | | | | | Symons (1876) gives details of a flood recorded upstream at Stratford-Upon-Avon. Potter (1978) reports that notable flooding did occur in the Midlands. It is likely that a notable event also occurred at Evesham. |
| **9** | 1830 | Jun | 26 | 14.00 | | | | | | |
| **10** | 1848 | Oct | 1 | 14.75 | 15.00 | | 14.25 | 14.25 | 14.38 | |

***Table 5.1*** *Historical flood data for the Avon at Evesham 1374 – 1848. Columns A to E present, where available, peak levels (feet), as given by sources A to E (see Appendices).*

**1.** Both Tindal (1794) and May (1845) refer to the exact location of the bridge said to have been damaged by a flood in 1374. Information regarding the location of the event is complete. Only the year of the flood is known. No level or flow data are available and ranking of the event is not possible.
The criteria based on source analysis described in Section 3.3 regarding the authenticity of the information have largely been satisfied. Neither author appears to have reason to fabricate the details of the event. Tindal was a Fellow of Trinity College, Oxford and May a local historian. Neither account is contemporary but May cites a chronicle of the time as his primary source. The two accounts appear to be independent since the descriptions of the event are different.

**2.** Savage (1929) reproduced an account taken from a parish register that describes flood damage to a bridge in Stratford-Upon-Avon. It is evident that a flood did occur on the River Avon but the occurrence of a notable flood at Evesham, although likely, is unconfirmed. Doubt, concerning the accuracy of the date given in the register was subsequently expressed since a notable flood had been recorded downstream at Tewkesbury almost exactly one year earlier. No level or flow data are available and ranking of the event is not possible.
The original account found in the parish register is contemporary, although the year the flood occurred seems to have been recorded in error. The parish of Welford-on-Avon is close to the bridge described in the register. The account is most likely to have been written by the vicar of the parish who is unlikely to have a reason to fabricate or exaggerate details of the event. The reliability of the information is thrown into doubt by the confusion surrounding the date of occurrence.

**3.** The detailed descriptions of the 1770 flood provided by May (1845) and Symons (1876) mean that the exact location of the event is not in doubt. The year and month of the event are documented by the latter. The day this notable flood occurred is recorded in a subsequent newspaper article. Symons provides enough information (an estimate of the peak level and a comparison with another event) to allow tentative ranking.
Although the accounts are not contemporary, May and Symons (who at that time was Secretary to the Meteorological Society) are both well qualified and motivated to record the events accurately. It appears that Symons' account has some similarity to the earlier account by May and is essentially derivative. There appears to be little reason to question the authenticity of May's description of the event.

**4.** Details of the flood are taken from the diary of the Vicar of Bengeworth. Information regarding the location and date of occurrence is complete. The flood was said to be within 14 inches of the 1770 flood. Tentative ranking is possible.
The original account is contemporary, written by a local clergyman and thought to be authentic.

**5.** A local attorney's memorandum book provides complete details of the location and date of occurrence. No flood level is given but Baylis (1985) interprets the description of the extent of the flood to suggest that the event peak was similar to that which occurred on $31^{st}$ December 1900. The level of uncertainty regarding this assumption means that ranking is not possible.
The original account is contemporary, written by a local man well qualified to record events accurately, and thought to be authentic.

**6.** All information regarding the location of the event is complete but only the year is given. Although no flood level is given, a tentative ranking is possible since comparison with other notable floods is given.
The information is taken from contemporary local newspapers and is thought to be authentic.

**7.** The description mentions flood damage at Evesham but the date information is incomplete. No level or flow information is available and ranking is not possible.
The source quoted by the BHS Chronology of Hydrological Events is a contemporary local newspaper and the information is thought to be authentic.

**8.** Details of an event on the River Avon are given and it is likely, but not certain, that a notable flood occurred at Evesham. Date information is complete. No level or flow information is available and ranking is not possible.
The source of the information provided by Symons (1876) is a local mill owner who had established a flood gauge board. The information is likely to be authentic.

**9.** Locational and date information is complete. An approximate flood level is given that allows tentative ranking.
The information given by Symons is considered to be authentic.

**10.** Locational and date information is complete and a peak flood level is given. Ranking is possible. The flood gauge board established by a builder's merchant in Evesham provides the primary data source for historic floods from 1848 – 1937 and the information is considered to be highly reliable.
Data from the gauge were provided by the Severn River Authority (SRA) and are considered authentic (Column $B_1$, Table 5.1). Credible information is also provided by a number of supplementary sources.

| | Where? | | | When? | | | Magnitude? | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Ref.** | River basin | Tributary | Location | Year | Month | Day | Ranking possible? | Level | Flow | Authenticity weighting? |
| **1** | ✔ | ✔ | ✔ | ✔ | | | | | | ✔ |
| **2** | ✔ | ✔ | | | | | | | | |
| **3** | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | | ✔ |
| **4** | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | | ✔ |
| **5** | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | | | | ✔ |
| **6** | ✔ | ✔ | ✔ | ✔ | | | ✔ | | | ✔ |
| **7** | ✔ | ✔ | ✔ | ✔ | ✔ | | | | | ✔ |
| **8** | ✔ | ✔ | | ✔ | ✔ | ✔ | | | | ✔ |
| **9** | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | | ✔ |
| **10** | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ | | ✔✔ |

***Table 5.2*** *Evaluation notes and tick boxes for historical flood data 1374-1848*

### 5.5.2 A ranked flood series

Appendix G presents the results of evaluating historical flood information collated for Evesham for the period 1374 – 1937, using a tick-box procedure. The graphical review of flood frequency curves using historical flood information (Section 4.5) requires that the flood series be ranked. It is evident from this evaluation that for a small number of historic floods there is insufficient information to enable this to be done. However, for the majority it is possible to include them in a list of ranked events with reasonable confidence.

It is important to allocate a realistic period of record to the historical information (Section 4.4.3). It is tempting here to include the notable floods that occurred in 1770, 1793 and 1801, since evaluation of the information relating to the events indicated that the data were considered authentic and sufficiently complete to make ranking possible. However, uncertainty regarding the magnitude of the floods of 1799, 1809 and 1821 (see Tables 5.1 and 5.2) means that these events cannot be included in the historic flood series. Therefore, the series is considered comprehensive from the event on 26th June 1830, but to take the date of the earliest flood as the start of the period of the historical record may introduce bias. It is reasonable to assume, given the level of interest in floods at that time, and the fact that no event appears to have been reported between the flood of 25th December 1821 and 26th June 1830, that the period between these two events was flood-free. The start date for the historic flood series used here therefore, is taken to be the 1st October 1822 (start of the 1822 water year).

Table 5.3 presents a tentative ranking (in descending order of magnitude) of the largest 20 floods, taken from the combined historical and systematic (formally gauged) records collated for the Avon at Evesham, for the period 1822 – 1999. The levels shown are largely those compiled by the Severn River Authority (Appendix B). They are given relative to zero level of the autographic recorder installed in 1937 (assumed to be 65 ft. AOD) to assist in the comparison between data from different sources. The peak flows provided in Table 5.3 have been taken from the systematic annual maximum record held at CEH Wallingford (Appendix H).

The graphical approach also requires that an informal estimate of the peak flow is made for historic floods, where this is unknown, to allow the data to be plotted. Volume IV of the Flood Studies Report (NERC, 1975) does list estimates of peak flow for historic floods on the Avon at Evesham. However, these appear unreliable when compared to the flow values assigned to the gauged level data.

| Rank | Date | Peak level (feet) | Peak flow ($m^3s^{-1}$) | Comments |
|---|---|---|---|---|
| **1** | **10 04 1998** | **16.1** | **427.0** | Level (Bye & Horner, 1998). Flow (NRFA – see Appendix H) |
| 2 | 31 12 1900 | 15.8 | | Highest flood level between 1/10/1848 – 9/1937 (see Appendix B) |
| 3 | 01 10 1848 | 15.0 | | |
| 4 | 11 11 1852 | 14.3 | | |
| 4 | 26 06 1830 | 14.3 | | Said to be equal to that of 11/11/1852 (Symons, 1876) |
| 6 | 25 10 1882 | 13.8 | | |
| **7** | **11 07 1968** | **13.5** | **361.9** | |
| **8** | **14 03 1947** | **13.5** | **356.2** | |
| 9 | 31 05 1924 | 13.5 | | |
| 10 | 21 10 1875 | 13.4 | | |
| 11 | 21 05 1932 | 13.3 | | |
| 12 | 09 03 1889 | 13.2 | | |
| 13 | 21 07 1875 | 12.8 | | |
| **14** | **08 02 1940** | **12.6** | **316.2** | |
| 15 | 27 12 1935 | 12.4 | | |
| 16 | 14 11 1875 | 12.3 | | Not an annual maximum flood |
| 17 | 24 02 1933 | 12.2 | | |
| 18 | 17 08 1879 | 12.1 | | |
| 19 | 14 05 1886 | 12.0 | | |
| 20 | 21 01 1896 | 11.9 | | |

Emboldened font is used to denote those flood events taken from the gauged (i.e. systematic) flow record. The flood peak level for the event on 26 06 1830 has been adjusted to be consistent with those compiled by the Severn River Authority.

***Table 5.3*** *The 'top 20' floods – Avon at Evesham (1822 – 1999)*

The ranked 'top 20' floods listed in Table 5.3 include post-1937 events (emboldened) for which gauged flow data are available. These flood peak flows, taken from the systematic record (see Appendix H), have been used here as a basis for estimating a peak flow for each of the historic floods. An approximate stage-discharge relationship was drawn up using the level and flow data available for the four events taken from the systematic record (Rank 1, 7, 8, 14 floods – Table 5.3). Peak flows were subsequently estimated using historical flood levels and this informal rating curve. Table 5.4 lists the 'top 19' annual maximum floods for the period 1822 – 1999 (water years 1822 – 1998 inclusive) with estimates of flow for the historic floods listed. The event recorded on 14th November 1875 (shown in Table 5.3) is not included since this is not an annual maximum flood. These data form the basis of the historical review of flood frequency curves constructed for the Avon at Evesham using the relatively short systematic record (1937 – 1999).

| Rank | Water year | Date | Peak level (feet) | Estimated peak flow ($m^3s^{-1}$) |
|---|---|---|---|---|
| **1** | **1997** | **10 04 1998** | **16.1** | **427** |
| 2 | 1900 | 31 12 1900 | 15.8 | 410 |
| 3 | 1848 | 01 10 1848 | 15.0 | 392 |
| 4 | 1852 | 11 11 1852 | 14.3 | 370 |
| 4 | 1829 | 26 06 1830 | 14.3 | 370 |
| 6 | 1882 | 25 10 1882 | 13.8 | 364 |
| **7** | **1967** | **11 07 1968** | **13.5** | **362** |
| **8** | **1946** | **14 03 1947** | **13.5** | **356** |
| 9 | 1923 | 31 05 1924 | 13.5 | 350 |
| 10 | 1875 | 21 10 1875 | 13.4 | 345 |
| 11 | 1931 | 21 05 1932 | 13.3 | 340 |
| 12 | 1888 | 09 03 1889 | 13.2 | 336 |
| 13 | 1874 | 21 07 1875 | 12.8 | 325 |
| **14** | **1939** | **08 02 1940** | **12.6** | **316** |
| 15 | 1935 | 27 12 1935 | 12.4 | 306 |
| 16 | 1932 | 24 02 1933 | 12.2 | 298 |
| 17 | 1878 | 17 08 1879 | 12.1 | 296 |
| 18 | 1885 | 14 05 1886 | 12.0 | 293 |
| 19 | 1895 | 21 01 1896 | 11.9 | 290 |

Emboldened font is used to denote those flood events taken from the gauged (i.e. systematic) flow record.

***Table 5.4*** *The 'top 19' annual maximum flood peaks (water years 1822 – 1998 inclusive)*

## 5.6 CONSTRUCTION OF FLOOD FREQUENCY CURVES

### 5.6.1 Introduction

Flood frequency curves for a gauged site (i.e. one with annual maximum data) can occasionally be based solely on the flood peak data available from the gauge (site analysis). However, the Flood Estimation Handbook (IH, 1999) recommends 'pooled analysis' for all but the longest of records or shortest of target return periods (Reed & Houghton-Carr, 1999). In the latter approach, annual maximum data taken from catchments defined to be hydrologically similar to the subject site are 'pooled' (Jakob *et al*., 1999). Here, 'site' and 'pooled' flood frequency curves have been constructed so that both may be reviewed in the light of historical information.

### 5.6.2 Site analysis

Annual maximum flood peak data taken from the gauge at the site of interest (Avon at Evesham) can be used to construct the flood frequency curve. Collation of flood peak data for the FEH supplemented earlier extractions of flood peak data undertaken at CEH Wallingford (Bayliss, 1999a). The record for Evesham used here comprised annual maximum data (water years) for the period 1937 – 1990 inclusive, extended to 1998 by using data supplied to the National River Flow Archive at CEH Wallingford by the Environment Agency (EA). This use of EA data to extend the record was only undertaken after comparison of CEH and EA data for a period of overlap between the two records. Annual maximum flood peak values for the two datasets were largely consistent from 1958 – 1990 inclusive indicating that, in this case, extending the series in this way was acceptable. Appendix H gives details of this combined annual maximum series (1937 – 1998 inclusive).

Construction of the site flood frequency curve used the FEH software WINFAP-FEH (IH, 1999) and followed the recommendations given in the Handbook. Figure 5.3 shows the flood frequency curve for the Avon at Evesham, fitted using the Generalised Logistic distribution (Robson, 1999b) to the gauged annual maximum series 1937 – 1998. The flood data are also plotted using the Gringorten formula, which allows a visual assessment of the goodness of fit.

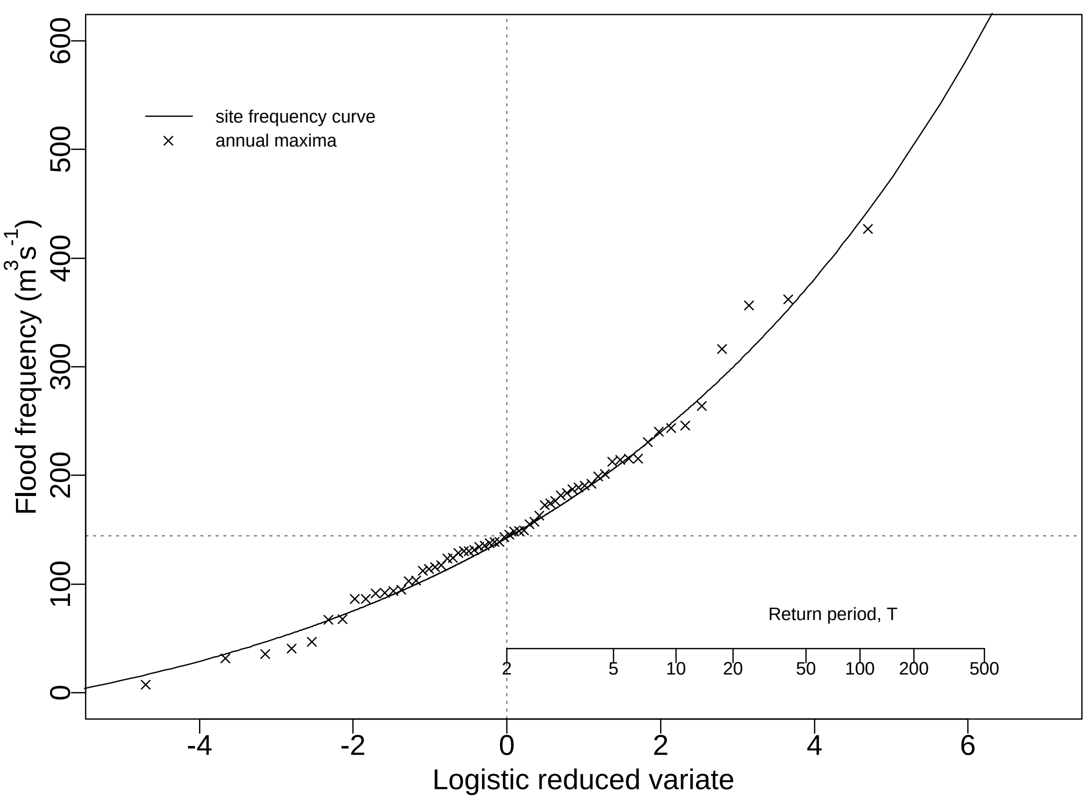



***Figure 5.3*** *Extreme value plot for the Avon at Evesham*

### 5.6.3 Pooled analysis

The FEH software WINFAP-FEH has been used to select an initial pooling-group by seeking those catchments that are essentially rural, and 'nearest' to the subject site with respect to their size, wetness and soil type. The software has assigned a similarity ranking according to the closeness of each catchment to the subject site in this 3-dimensional space (Jakob *et al.*, 1999). The FEH rule of thumb is that the combined record length of sites in the pooling-group should be at least five times the target return period (the 5T rule). The initial pooling-group selected for the Avon at Evesham was based on a nominal target return period of 100 years and comprises 18 station records and 520 station-years of annual maximum data (Figure 5.4).

WINFAP-FEH Projectfile - [Pooling group details for 54002 (Avon @ Evesham)]

File Options Single site Pooled analysis View Window Help

| | Station | Years | L-CV | L-Skewnes | L-Kurtosis | Discordancy | Distance |
|---|---|---|---|---|---|---|---|
| 1 | 33002 (Bedford Ouse @ Bedford) | 34 | 0.213 | -0.009 | 0.156 | 0.375 | 0.413 |
| 2 | 33009 (Bedford Ouse @ Harrold Mill) | 41 | 0.212 | 0.058 | 0.204 | 0.135 | 0.416 |
| 3 | 40003 (Medway @ Teston) | 30 | 0.237 | 0.253 | 0.172 | 0.478 | 0.516 |
| 4 | 33037 (Bedford Ouse @ Newport Pagnell) | 24 | 0.191 | -0.213 | 0.105 | 1.882 | 0.585 |
| 5 | 27008 (Swale @ Leckby Grange) | 28 | 0.118 | 0.080 | 0.089 | 0.814 | 0.734 |
| 6 | 31004 (Welland @ Tallington) | 27 | 0.226 | 0.220 | 0.305 | 0.472 | 0.799 |
| 7 | 28024 (Wreake @ Syston Mill) | 25 | 0.264 | 0.367 | 0.369 | 1.091 | 0.882 |
| 8 | 24009 (Wear @ Chester le Street) | 15 | 0.146 | 0.172 | 0.006 | 2.381 | 0.883 |
| 9 | 31005 (Welland @ Tixover) | 32 | 0.290 | 0.244 | 0.229 | 0.235 | 0.892 |
| 10 | 27009 (Ouse @ Skelton) | 36 | 0.144 | 0.147 | 0.161 | 0.531 | 0.901 |
| 11 | 36001 (Stour @ Stratford st Mary) | 40 | 0.268 | 0.240 | 0.311 | 0.276 | 0.951 |
| 12 | 34006 (Waveney @ Needham Mill) | 11 | 0.507 | 0.407 | 0.299 | 4.158 | 0.972 |
| 13 | 36015 (Stour @ Lamarsh) | 21 | 0.226 | -0.105 | 0.208 | 1.270 | 0.986 |
| 14 | 22001 (Coquet @ Morwick) | 30 | 0.239 | 0.232 | 0.193 | 0.223 | 0.988 |
| 15 | 54010 (Stour @ Alscot Park) | 32 | 0.243 | 0.118 | 0.227 | 0.047 | 1.028 |
| 16 | 68001 (Weaver @ Ashbrook) | 56 | 0.225 | 0.353 | 0.327 | 1.107 | 1.043 |
| 17 | 41007 (Arun @ Park Mound) | 15 | 0.371 | 0.336 | 0.452 | 1.663 | 1.057 |
| 18 | 33005 (Bedford Ouse @ Thornborough Mill) | 23 | 0.132 | -0.095 | 0.147 | 0.861 | 1.057 |
| 19 | | | | | | | |
| 20 | Total | 520 | | | | | |
| 21 | Weighted means | | 0.219 | 0.133 | 0.202 | | |

***Figure 5.4*** *Initial pooling group - ordered according to similarity to the subject site (from WINFAP-FEH)*

The software suggests that the initial selection is strongly heterogeneous and that review of the pooling group is essential. Review of flood peak records and catchment descriptor information for all members of the pooling-group is recommended by the FEH (Reed *et al.*, 1999) and was undertaken here. The record for the Waveney at Needham Mill (34006) has been singled out by WINFAP-FEH for closer examination (highlighted in grey) since the distribution of annual maxima for this station, as determined by a discordancy measure, is strongly different from the group average. Examination of the annual maximum data for this site reveals however, that this is the result of a single flood event (17$^{th}$ September 1968) being substantially bigger than any other flood in the relatively short 11-year series. In this case it is inappropriate to reject the station from the pooling group on this basis.

For those catchments with peaks-over-threshold (POT) data, the date of flood occurrence can be analysed to provide a measure of flood seasonality (Bayliss & Jones, 1993). Catchments that are hydrologically similar are unlikely to have distinct signatures of flood seasonality. WINFAP-FEH provides a visual comparison of flood seasonality for pooling-group members with POT data. In this case the plot indicated that winter is the dominant flood season for all group members.

WINFAP-FEH also provides diagnostic plots that allow visual comparison of catchment descriptor values for all sites in the pooling group. The ‘distance’ between the subject site and each of those in the pooling group (see Figure 5.4) is a measure of hydrological similarity based on three catchment descriptors. In addition to a comparison of values of these descriptors, the diagnostic plots provide comparisons of other descriptor values which may help identify members of the group that are hydrologically dissimilar.

The initial pooling group includes the Coquet at Morquet (22001) – an upland catchment in north-east England. The catchment descriptor PROPWET denotes the proportion of time that soils are at, or near, field capacity (Bayliss & Morris, 1999). Values of PROPWET for the Avon at Evesham (0.29) and the Coquet at Morquet (0.44) are notably different. As a consequence, catchment 22001 was seen to be an inappropriate member of the pooling group and as such was discarded (i.e. selected by the user and deleted). Figure 5.4 shows the selection (highlighted in black) of the station record prior to deletion. The removal of the record for the River Coquet reduced the total number of station-years within the pooling group to 490. Although this is less than the total record prescribed by the 5T rule, FEH guidelines suggest that 4.9T station-years is adequate (Reed *et al.*, 1999). In this case therefore, no replacement record was brought into the pooling group.

A pooled flood frequency curve was produced for the revised pooling group using the Generalised Logistic distribution provided by the WINFAP-FEH software (Figure 5.5). For comparison, the flood frequency curve produced using data provided by the initial pooling group has also been plotted. [Note that both curves have been adjusted for urbanisation, see Section 5.6.4]. Removal of the record for station 22001 from the pooling group has had a minimal effect. This is largely due to its position ($14^{th}$) according to the ranked similarity of group members (Figure 5.4). Greater weight, in the production of the pooled flood frequency curve, is given to those catchments that are defined to be ‘nearer’ the subject site in the 3-dimensional space used to determine hydrological similarity.

### 5.6.4 Adjustment for urbanisation

The FEH recommends a two-stage approach to flood frequency estimation. Firstly, estimates are produced assuming the subject site is essentially rural. Secondly, where the subject site is urbanised, the estimates may be subsequently adjusted. It follows therefore, that the catchments included in the pooling are all essentially rural - that is they have an URBEXT value of less than 0.025 (Reed *et al.*, 1999). The Avon at Evesham has an $URBEXT_{1990}$ value of 0.042 and is categorised as slightly urbanised (Bayliss & Scarrott, 1999). It is not included in its own pooling group and an adjustment to the flood frequency curve is appropriate.

Since the gauged data for the Avon at Evesham used to compute the median annual flood (QMED) include the residual effect of urbanisation, an adjustment of QMED is not necessary. Adjustment of the pooled flood growth curve is, however, recommended. An urban adjustment factor (Reed & Robson, 1999) based on the FEH index of urban extent (URBEXT) can be applied to obtain the urban pooled flood frequency curve. The catchment to Evesham has an $URBEXT_{1990}$ value of 0.042. As a consequence, both the initial and revised pooled flood frequency curves (Figure 5.5) include an adjustment for urbanisation. Comparisons of adjusted and unadjusted curves indicated that, in this case, this had little effect. This result is consistent with expectations since the catchment is only slightly urbanised.

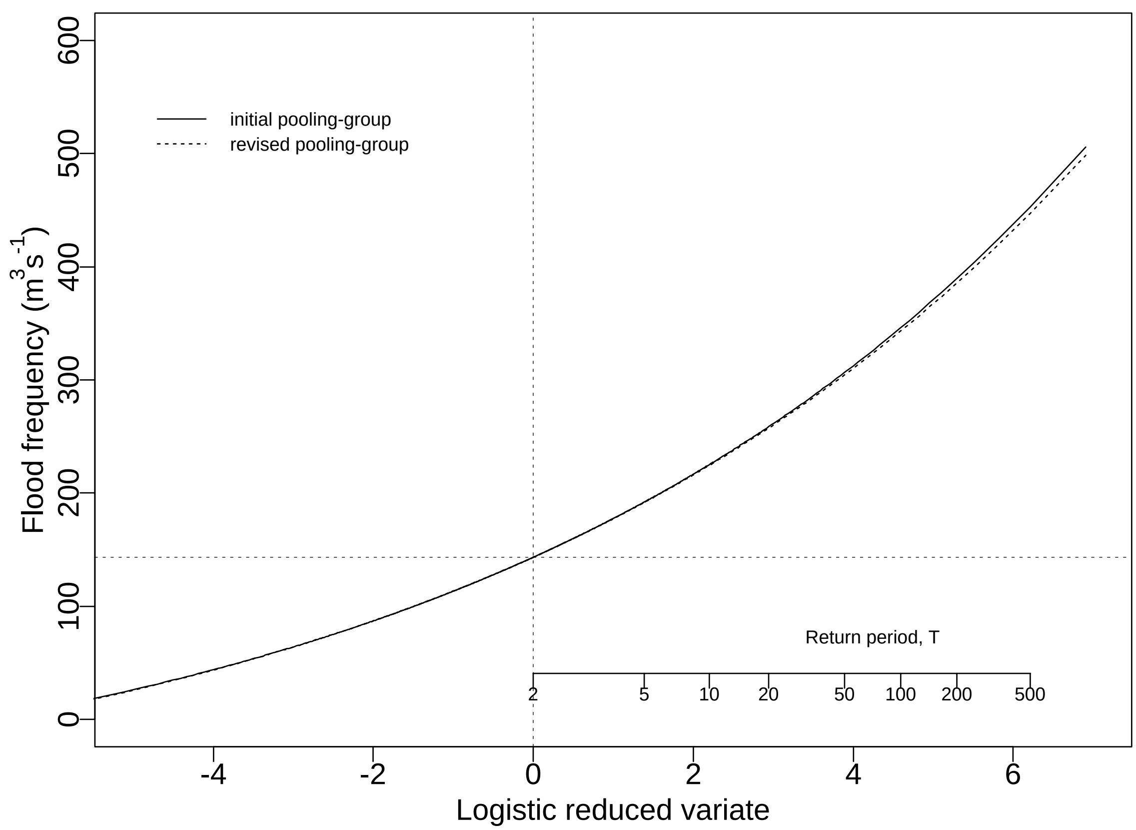



***Figure 5.5*** *Flood frequency curves based on initial and revised pooling groups – adjusted for urbanisation*

## 5.7 REVIEW OF FLOOD FREQUENCY CURVES

### 5.7.1 Approach

Section 4.5 recommends an informal graphical approach for assessing what the historical data indicate about the flood frequency curve derived by conventional analysis. The use of pooling-groups and historical flood information can be seen as alternative ways of augmenting relatively short gauged records in the derivation of flood frequency curves. However, the incorporation of historical data using a graphical procedure has the advantage that not only can flood frequency curves produced by site analysis be reviewed, but also those derived by pooled analysis. Data from the Avon at Evesham are used to illustrate the review of both site and the pooled flood frequency curves.

There has been much discussion in the literature regarding appropriate plotting positions for historical flood data. The guidance given here (Section 4.5.4) describes how the Gringorten formula can be used to plot the largest floods from the combined historical and systematic (formally gauged) record. The use of plotting formulae that allow the largest floods from the combined records, along with those from the systematic record that fall below the extreme-flood threshold (used here to define ‘largest’), are given as an alternative.

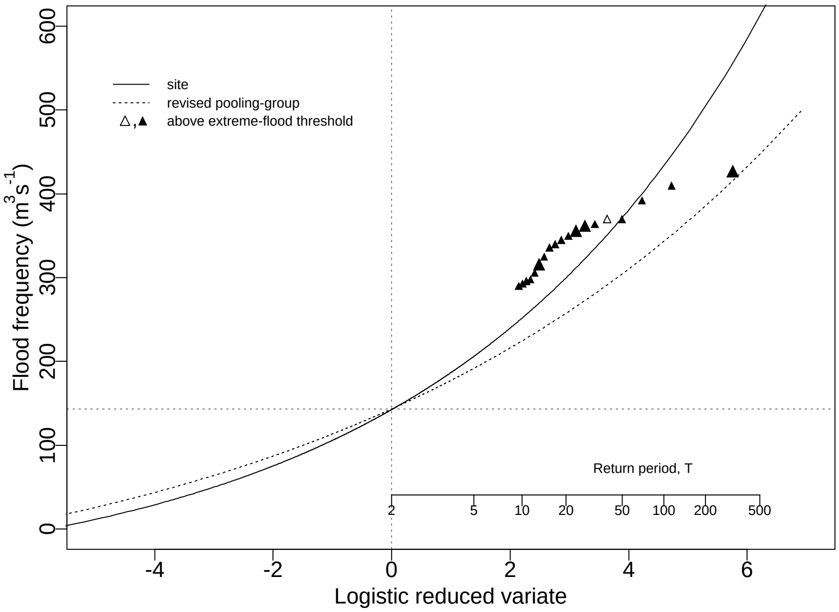
### 5.7.2 Comparison of frequency plotting positions

Figure 5.6a shows flood frequency curves constructed using site and pooled analysis without reference to historical data. The largest 19 annual maximum floods (triangles), above an arbitrarily chosen extreme-flood threshold, have also been plotted using the Gringorten formula.

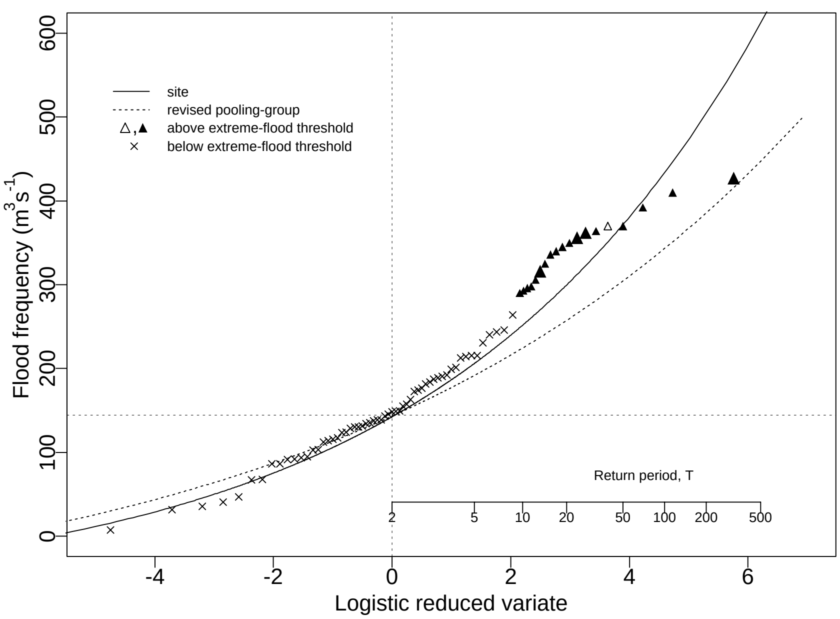
The use of alternative formulae (see Section 4.5.4) to assign frequency plotting positions is illustrated in Figure 5.6b. Firstly, Equation 4.4a has been used to calculate plotting positions for floods that have been taken from the combined historical and systematic records (1822 – 1998 inclusive) and are above the extreme-flood threshold. Secondly, annual maximum floods below the extreme-flood threshold, taken from the systematic record (1937 – 1998 inclusive), have been plotted using Equation 4.4b.

As expected differences between Figures 5.6a and 5.6b, with respect to the plotting positions for the events above the extreme-flood threshold, are very small. However, as Section 4.5.4 explains, the advantage of using Equations 4.4 is that they allow the systematic data below the threshold to be plotted in a way that is consistent with the plotting of those events above the threshold.

A comparison of the results including the historical information (Figure 5.6b) with those not using this information (Figure 5.3) indicates that there is broad agreement. Both sets of plotted points agree well with the site frequency curve, but there is a discernable effect




(a)




(b)

***Figure 5.6*** *Site and pooled flood frequency curves together with the 19 annual maximum floods above the extreme-flood threshold (triangles), taken from the combined historical and systematic records (1822 – 1998 incl.), and plotted using the Gringorten formula in (a) and Equation 4.4a in (b). Annual maximum floods below the extreme-flood threshold (crosses) are also plotted in (b) using Equation 4.4b. N.B. Solid triangles indicate that the source of the data is 'very reliable' and open triangles 'reliable'. Triangle size increases according to the completeness of the information on which the estimate of peak flow is based (see symbol scheme – Box 3.1, p. 14)* from the inclusion of the historical information. In addition to the most obvious changes in the points above the extreme-flood threshold, this effect is perhaps most readily seen in the points from the systematic record which are just below the threshold: these points are assigned slightly lower return periods than if the historical information is not used.

### 5.7.3 Review

Since there is generally greater scope for inadvertently omitting an authentic flood from the historical series, rather than including a spurious one, particular caution needs to be exercised where historical data indicate that the frequency curve may be overestimating flood magnitudes. Before lowering the curve the analyst needs to be certain that the historical series is complete and representative of the current flood regime.

Where historical data indicate that the flood frequency curve may be underestimating flood magnitudes, the evaluation of the historical information and the estimation of flows from historic levels should be checked. If no error or bias is found, the preferred flood frequency curve should be adjusted to gain better agreement with the historical data. Section 4.5.5 suggests how a flood frequency curve constructed using conventional analysis might be adjusted in the light of historical information.

If the plot shows reasonable accord between the historical data, and the flood frequency curve constructed using data from the systematic record by conventional analysis, the latter can be used with increased confidence. Here the plots showing the largest 19 floods in a combined historical and systematic record of 177 years, (Figures 5.6a and 5.6b) suggests that the pooled analysis may be underestimating flood frequency at Evesham. In such a situation (i.e. when the historical analysis indicates that the conventional analysis is underestimating flood frequency) adjustment is strongly advisable. In this instance, it is reasonable to adopt the flood frequency curve based on the site analysis, which agrees well with the historical data. Use of the site flood frequency curve would assign a return period of approximately 100 years to the Easter 1998 flood of 427 $m^3s^{-1}$.

# 6 Discussion and conclusions

The collation of information on historic floods may appear daunting. IH Report No. 46 (Potter, 1978) provides detailed guidance regarding the location of information on hydrological events that occurred in England and Wales as far back as the Norman Conquest and beyond. This report brings the guidance up-to-date by including advice on how the use of the World Wide Web and electronic newspapers can provide useful information on historic floods. Searching for information on floods that occurred before the early 18$^{th}$ century is only likely to reveal highly descriptive accounts. The guidance given here relates primarily to sources that are likely to give useful data on floods occurring from the early 1700s.

A rigorous evaluation of the historical data collated is encouraged. In particular, it is important that the completeness of the information used to estimate the peak flow and the authenticity of the data are assessed. The evaluation procedure used to determine authenticity is based on the principles of 'source analysis' developed by historians in the early 19$^{th}$ century. A tick-box procedure is suggested to encourage a meticulous approach and to identify those historic events that 'score well'. By adopting a suitable symbol scheme, greater visual weight can be given to appropriate floods when using the historical data in a graphical review of the flood frequency curve.

Methods for incorporating historical data into flood frequency estimates are reviewed. The use of paleoflood data is also discussed. Review of some of the formal methods that have been suggested in the literature is undertaken. Graphical methods are considered in more detail and an alternative to the use of the Gringorten formula for plotting historical data is put forward. The advantage of using these alternative formulae is that flood data from the systematic (i.e. gauged) record that are below the extreme-flood threshold, can be plotted in a way that is consistent with the use of the other data (i.e. the historical and the systematic data that exceed the threshold).

The recommended approach is that the analyst should:

- Collate and evaluate the historical flood information
- Undertake a detailed flood frequency analysis and derive a preferred (conventional) flood frequency curve without using historical data
- Use a graphical approach to re-appraise the preferred flood frequency curve in the light of the historical data.

If the plot shows reasonable accord between the historical data and the flood frequency curve constructed using conventional analysis, the latter can be retained with increased confidence. In other circumstances it may be appropriate to adapt the flood frequency curve. A number of possible strategies for adaptation are suggested in Section 4.5.6.

A case study – the River Avon at Evesham – is used to illustrate the guidance given. Historic flood levels had been recorded by a builder's merchant since 1848. These form the basis of the historical data used. Local newspapers, contemporary academic journals and local histories provided supplementary and corroborative information. A rigorous evaluation of the information, in terms of completeness and authenticity, was undertaken using a tick-box procedure. Flood frequency curves were constructed using the site and pooled analysis procedures described in the Flood Estimation Handbook, and were subsequently reviewed using historical flood information.

The review suggested that the pooled analysis may be underestimating flood frequency at Evesham. In such a situation (i.e. when the historical analysis indicates that the conventional analysis is underestimating flood frequency) adjustment is strongly advisable. In this instance, it was reasonable to adopt the flood frequency curve based on the site analysis, which agrees well with the historical data. Use of the site flood frequency curve would assign a return period of approximately 100 years to the Easter 1998 flood of 427 $m^3s^{-1}$.

In conclusion, this report offers up-to-date guidance on the collation of historical flood data. It encourages a rigorous evaluation of the data gathered. The review of methods for incorporating historical data into flood frequency estimates exposes the main issues and concludes by supporting a graphical approach. The case study is used to illustrate the guidance given but it is hoped that the presentation of a historical flood chronology for the Avon at Evesham will be of benefit to others with an interest in this river.

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# APPENDICES

The datasets used to establish a historical flood chronology for the River Avon at Evesham are given in Appendices A to H. These datasets are too large to be included within the main body of the report, but are presented here since they represent important material used in the case study described in Chapter 5. The collation of historical flood information can sometimes be difficult and time consuming. The inclusion of tabulated flood data, and extracts from academic journals and newspapers, serves to benefit others seeking to gather historical flood data for the Avon catchment.

## APPENDIX A

### Source

Symons, G.J. 1876. On the floods in England and Wales during 1875, and on Water Economy. Proceedings of the Institution of Civil Engineers, Vol. 45, 1-14.

### Extract

*At Stratford-on-Avon a flood board was placed by the bank of the river at the Stratford flour mills at the beginning of the present century, and every occasion when the floods have risen to 4 feet above the weir have been recorded. Messrs. C. Lucy and Nephew, in sending the following list, remark, that of a total of ten floods which have exceeded 4 feet in height, four were in 1875, being the only instance where more than one flood has reached over 4 feet in the same year.*

| | | Feet. | Inches. |
|---|---|---|---|
| *1801* | *(Date unknown)* . . . | *7* | *2.5* |
| *1821* | *December 25th* . . . | *5* | *8.25* |
| *1848* | *October 1st* . . . | *6* | *4.25* |
| *1852* | *November 12th* . . . | *5* | *10.5* |
| *1853* | *July 15th* . . . . | *5* | *5* |
| *1872* | *December 14th* . . . | *5* | *4* |
| *1875* | *July 22nd* . . . . | *6* | *8* |
| “ | *October 12th* . . . . | *4* | *9* |
| “ | “ *21st* . . . . | *6* | *0.5* |
| “ | *November 14th* . . . | *5* | *9* |

*Observations at Evesham, 16 miles lower down the river, gave nearly the same results, the slight differences probably being due to the tributaries the Avon receives between Stratford and Evesham.*

| | | Above ordinary level. | |
|---|---|---|---|
| | | *Feet.* | *Inches.* |
| *1770* | *November.-The highest flood within living memory; it reached almost up to the keystone of the middle arch of the bridge, of which no accurate record exists, probably* | *15* | *0* |
| *1830* | *June 26th.-Violent thunder-storm; the river during the night rose from its usual level to about* . . | *14* | *0* |
| *1848* | *October 1st.-A three days' rain caused the river to rise rapidly; the flood can only have been second to that of 1770* . . . . . . . | *14* | *9* |
| *1852* | *November 11th.-Greatest height* . . . | *14* | *0* |
| *1872* | *January 18th.-A flood of long duration; for seventy hours* | | |

| | | | | |
|---|---|---|---|---|
| | *it exceeded . . . . . .* | | *7* | *0* |
| | *And its maximum was . . . . .* | | *8* | *9* |
| *1875* | *July 22nd.- Maximum at 4 P.M.* | *. . .* | *12* | *6* |
| “ | *October 10th. “ 4 P.M.* | *. . .* | *9* | *6* |
| “ | “ *21st. “ 4 A.M.* | *. . .* | *13* | *1* |
| “ | “ *28th. “ 4.30 P.M.* | *. . .* | *4* | *6* |
| “ | *November 7th. “ 8 A.M.* | *. . .* | *8* | *6* |
| “ | “ *12th. “ 4 A.M.* | *. . .* | *10* | *0* |
| “ | “ *14th. “ 3 P.M.* | *. . .* | *12* | *0* |

**Comments**

The extract taken from page 7 is reproduced *verbatim*, except for the flood levels where fractions of an inch were used. They are expressed here using the decimal equivalent of the fractions.

The flood of 18th January 1872, which at its maximum was said to be 8ft. 9in., does not appear in the other flood series. However, included in the floods listed by the Evesham Journal on 12th January 1901 (taken from Burlingham’s record) is an event that was said to have occurred on 24th January 1872, that has the same peak level of 8ft. 9in. It is likely therefore that, since Symons also refers to the duration of the flood, the 18th January 1872 relates to the start of the event, rather than its peak.

**APPENDIX B**

**Source**

Severn River Authority.

**Data**

| Year | Month | Day | (ft. AOD) | (g.h. ft.) | Flow ($m^3s^{-1}$) |
|---|---|---|---|---|---|
| 1848 | Oct | 1 | 80.0 | 15.00 | |
| 1852 | Nov | 11 | 79.3 | 14.30 | |
| 1853 | Jul | 15 | 76.2 | 11.20 | |
| 1867 | Mar | 24 | 76.8 | 11.80 | |
| 1872 | Dec | 18 | 76.6 | 11.60 | |
| 1872 | Jan | 24 | 74.5 | 9.50 | |
| 1872 | Nov | 24 | 75.0 | 10.00 | |
| 1875 | Jan | 12 | 74.3 | 9.30 | |
| 1875 | Jul | 21 | 77.8 | 12.80 | |
| 1875 | Nov | 7 | 74.3 | 9.30 | |
| 1875 | Nov | 14 | 77.3 | 12.30 | |
| 1875 | Oct | 12 | 75.2 | 10.20 | |
| 1875 | Oct | 21 | 78.4 | 13.40 | |
| 1878 | Dec | 29 | 74.5 | 9.50 | |
| 1878 | May | 11 | 75.3 | 10.30 | |
| 1878 | Nov | 11 | 74.8 | 9.80 | |
| 1879 | Aug | 17 | 77.1 | 12.10 | |
| 1880 | Dec | 30 | 73.6 | 8.60 | |
| 1880 | Feb | 20 | 74.3 | 9.30 | |
| 1880 | Jul | 17 | 73.9 | 8.90 | |
| 1880 | Nov | 16 | 74.3 | 9.30 | |
| 1880 | Oct | 6 | 76.3 | 11.30 | |
| 1881 | Dec | 19 | 74.0 | 9.00 | |
| 1881 | Feb | 11 | 73.3 | 8.30 | |
| 1882 | Jan | 10 | 73.3 | 8.30 | |
| 1882 | Mar | 1 | 73.2 | 8.20 | |
| 1882 | Nov | 6 | 74.7 | 9.70 | |
| 1882 | Oct | 25 | 78.8 | 13.80 | |
| 1883 | Feb | 11 | 75.5 | 10.50 | |
| 1883 | Jan | 30 | 73.1 | 8.10 | |
| 1886 | May | 14 | 77.0 | 12.00 | |
| 1889 | Mar | 9 | 78.2 | 13.20 | |
| 1894 | Mar | 15 | 75.0 | 10.00 | |
| 1895 | Nov | 14 | 73.0 | 8.00 | |
| 1896 | Jan | 16 | 73.2 | 8.20 | |

| | | | | | |
|---|---|---|---|---|---|
| 1896 | Jan | 21 | 76.9 | 11.90 | |
| 1900 | Dec | 30 | 80.8 | 15.80 | |
| 1900 | Feb | 16 | 75.6 | 10.60 | |
| 1908 | Apr | 29 | 75.7 | 10.70 | |
| 1910 | Dec | 4 | 75.3 | 10.30 | |
| 1912 | Aug | 27 | 76.2 | 11.20 | |
| 1912 | Jan | 22 | 75.0 | 10.00 | |
| 1914 | Dec | 31 | 76.3 | 11.30 | |
| 1918 | Apr | 22 | 74.0 | 9.00 | |
| 1918 | Jan | 20 | 75.5 | 10.50 | |
| 1920 | Apr | 10 | 75.8 | 10.80 | |
| 1924 | May | 31 | 78.5 | 13.50 | |
| 1926 | Jan | 2 | 75.2 | 10.20 | |
| 1928 | Jan | 2 | 74.8 | 9.80 | |
| 1932 | May | 1 | 76.1 | 11.10 | |
| 1932 | May | 15 | 74.7 | 9.70 | |
| 1932 | May | 21 | 78.3 | 13.30 | |
| 1933 | Feb | 24 | 77.2 | 12.20 | |
| 1935 | Dec | 27 | 77.4 | 12.40 | |
| 1935 | Nov | 18 | 74.0 | 9.00 | |
| 1939 | Jan | 27 | 75.4 | 10.40 | 227.7 |
| 1939 | Oct | 20 | 74.7 | 9.70 | |
| 1940 | Feb | 8 | 77.6 | 12.60 | 314.4 |
| 1940 | Nov | 22 | 74.3 | 9.30 | 187.2 |
| 1941 | Jan | 23 | 73.7 | 8.70 | 167.4 |
| 1941 | Jan | 26 | 73.4 | 8.40 | 160.0 |
| 1942 | Jan | 25 | 74.2 | 9.20 | 183.5 |
| 1943 | Feb | 1 | 74.7 | 9.70 | 201.9 |
| 1947 | Mar | 14 | 78.5 | 13.50 | 362.5 |
| 1947 | Mar | 18 | 76.3 | 11.30 | 257.4 |
| 1950 | Feb | 4 | 73.2 | 8.20 | 154.9 |
| 1950 | Nov | 22 | 73.6 | 8.60 | 166.2 |
| 1951 | Apr | 10 | 73.1 | 8.10 | 153.8 |
| 1955 | Mar | 27 | 74.4 | 9.40 | 190.9 |
| 1955 | May | 18 | 73.8 | 8.80 | 169.4 |
| 1959 | Jan | 7 | 73.8 | 8.80 | 171.1 |
| 1959 | Jan | 18 | 73.4 | 8.40 | 161.1 |
| 1959 | Jan | 23 | 75.8 | 10.80 | 240.7 |
| 1960 | Dec | 4 | 75.1 | 10.10 | 216.6 |
| 1960 | Jan | 25 | 75.8 | 10.80 | 242.4 |
| 1960 | Jan | 29 | 74.8 | 9.80 | 205.6 |
| 1965 | Dec | 10 | 73.1 | 8.10 | 152.4 |
| 1968 | Jan | 14 | 74.5 | 9.50 | 191.7 |
| 1968 | Jul | 12 | 78.5 | 13.50 | 371.0 |
| 1969 | Mar | 14 | 74.6 | 9.60 | |

**Comments**

In the early 1970s, the Severn River Authority (SRA) took flood records kept by Messrs. H. Burlingham & Co, carefully reduced the levels to Newlyn datum, and produced a subset of 55 events that exceeded a threshold level of 73 m AOD. A further 25 events above the threshold were extracted from the early autographic record (i.e. to September 1969) to augment these historic flood levels. This combined level series is listed in column 4 of the above table, where values are in decimal feet and are relative to the datum at Newlyn.

To assist comparisons with other historic flood levels, which tend to be relative to 'ordinary' or 'summer' level, the SRA data are also shown relative to the equivalent of zero height on the autographic gauge (assumed to be 65.0 ft. AOD). The levels in column 5 therefore, are based on the SRA data and shown relative to gauge height (g.h.) in decimal feet.

For the flood levels taken from the autographic record, the SRA also provided estimates of the flood flows ($ft^3s^{-1}$), which are shown in the final column in $m^3s^{-1}$.

## APPENDIX C

### Source

Southall, H. 1895. Floods in the West Midlands. Quarterly Journal of the Royal Meteorological Society, Vol. XXI, 28-39.

### Extract

*EVESHAM*

| | | *ft.* | *in.* | | | *ft.* | *in.* |
|---|---|---|---|---|---|---|---|
| *1848* | *October 1* | *14* | *3* | *1875* | *October 21* | *12* | *7.5* |
| *1852* | *November 11* | *13* | *6* | *1875* | *July 21* | *12* | *0.5* |
| *1882* | *October 25* | *13* | *0* | | | | |

*FLOODS AT TEWKESBURY*

*Dyke's History of Tewkesbury mentions high floods on the Severn on July 19th, 1587, when a sudden inundation overflowed the meadows to such an extent that the inhabitants were compelled to leave the loaded carts behind them as they went to gather the hay; and so great was the accumulation of hay that "the townsmen were constrained with pitchforks and long poles to stand on the bridge of wood to break the cocks, lest the bridge should be carried away by the force of them.*

### Comments

These extracts taken from pages 38 and 39 are reproduced *verbatim*, except for the flood levels where fractions of an inch were used. They are expressed here using the decimal equivalent of the fractions.

**APPENDIX D**

**Source**

Evesham Journal 12th January 1901

**Extract**

*There has been considerable discussion as to the relative height of last week's inundation* [31st December 1900] *and that of 1848, but there can be no doubt that on Monday week the water was no less than 9in. higher than it was in 1848. The following authentic list of floods from that date is very interesting…*

*1848, October 1, 14ft. 3in.*
*1852, November 11, 13ft. 6in.*
*1853, July 10, 10ft. 5in.*
*1867, March 24, 11ft. 0.5in.*
*1872, January 24, 8ft. 9in.*
*1872, February 20, 6ft. 0.5in.*
*1872, November 3, 7ft. 2in.*
*1872, November 24, 9ft. 3in.*
*1872, November 27, 7ft. 10in.*
*1872, December 18, 10ft. 10in.*
*1875, January 12, 8ft. 7in.*
*1875, July 21, 12ft. 0.5in.*
*1875, October 10, 9ft. 1in.*
*1875, October 12, 9ft. 5in.*
*1875, October 21, 12ft. 7.5in.*
*1875, October 28, 4ft. 6in.*
*1875, November 7, 8ft 6in.*
*1875, November 12, 9ft. 6.5in.*
*1875, November 14, 11ft. 6.5in.*
*1878, May 9, 8ft 4in.*
*1878, May 11, 9ft. 7in.*
*1878, November 11, 9ft.*
*1878, December 29, 8ft. 9in.*
*1879, June 17, 5ft. 10in.*
*1879, August 3, 4ft. 9in.*
*1879, August 17, 11ft. 4in.*
*1879, August 20, 7ft. 8.5in.*
*1880, February 20, 8ft. 6in.*
*1880, July 14, 7ft. 3in.*
*1880, July 17, 8ft. 1.25in.*
*1880, September 20, 6ft.*
*1880, October 6, 10ft. 7.5in.*
*1880, November 16, 8ft. 6in.*
*1880, December 27, 5ft. 9in.*
*1880, December 30, 7ft. 9.5in.*
*1881, January 10, 7ft. 1.5in.*
*1881, February 11, 7ft. 6in.*
*1881, February 15, 7ft. 2in.*
*1881, December 19, 8ft. 3in.*
*1882, January 10, 7ft. 6.5in.*
*1882, March 3, 7ft. 5in.*
*1882, October 24, 13ft.*
*1882, November 6, 8ft. 11in.*
*1883, January 30, 7ft. 4in.*
*1883, February 4, 7ft. 4in.*
*1883, February 11, 9ft. 9in.*
*1886, May 14, 11ft. 3in.*
*1887, January 11, 7ft. 9in.*
*1887, January 21, 10ft. 6in.*
*1889, March 9, 12ft. 5in.*
*1889, April 11, 7ft. 4in.*
*1894, November 22, 9ft. 4in.*
*1895, January 21, 11ft.*
*1897, February 6, 11ft. 8in.*
*1900, February 17, 9ft. 1in.*
*1900, February 20, 9ft. 10in.*
*1900, December 31, 15ft.*

**Comments**

This extract is reproduced *verbatim*, except for the flood levels where fractions of an inch were used. They are expressed here using the decimal equivalent of the fractions.

The event of November $14^{th}$ 1875 appeared twice in the list published in the Evesham Journal of January $12^{th}$ 1901. The observation is not repeated in the series given here.

The levels have, almost certainly, been taken from the records kept by Messrs. H. Burlingham & Co. The datum is unknown, but is likely to have been zero height on the gauge board used by Burlingham.

## APPENDIX E

### Source

Evesham Journal 16th April 1998

### Extract

*Floods, like any other phenomena, spark off endless debates on records, but this year's "Easter Flood" in Evesham was the highest ever, topping the "New Century Flood" by at least 6in.*

*The Avon last Friday afternoon peaked at just over 17ft (or 5.19 metres), which is well above the century's previous record level…*

*The flooding top ten*
*Previous top flood levels were:*

- *December 30, 1900 - 15.18ft.*
- *October 1, 1848 - 14.38ft.*
- *November 11, 1852 – 13.68ft.*
- *October 25, 1882 – 13.18ft.*
- *July 11, 1968 – 12.88ft.*
- *March 14, 1947 - 12.88ft.*
- *May 31, 1924 - 12.88ft.*
- *October 21, 1875 – 12.78ft.*
- *May 21, 1932 – 12.68ft.*
- *March 9, 1889 – 12.58ft.*

### Comments

This extract is reproduced *verbatim* except for an error in the list of "previous top flood levels". The original article listed an event on November 11, 1952, but should have read November 11, 1852. No flood event was recorded in the gauged record on that day in 1952, whereas an event of roughly the same magnitude is listed on November 11, 1852 by the other sources (Appendices A-D).

The reference to a peak level of "just over 17ft" for the Easter 1998 flood is confusing. The article states that it exceeded the previous highest "by at least 6in." but lists the flood of December 31st 1900 as recording a peak level of 15.18ft (a difference of nearly two feet). Presumably the Easter 1998 level relates to a different datum to that which applies to those given in the 'top ten' list.

**APPENDIX F**

**Sources**

Appendices A to E are brought together to facilitate cross-referencing between all the principal datasets. Flood levels, and additionally flows in the case of dataset B (marked $B_2$), are presented in columns A to E - labelled to be consistent with the appendices. The original sources are:

A Symons (1876)

B Severn River Authority (c. 1970)

C Southall (1895)

D Evesham Journal (12 January 1901)

E Evesham Journal (16 April 1998)

**Data**

| **Ref.** | Year | Month | Day | A | $B_1$ | $B_2$ | C | D | E | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 1374 | | | | | | | | | Tindal (1794) and May (1845) both refer to a flood in 1374 that damaged a bridge between Bengeworth and Evesham. |
| **2** | 1587 | Jul | 19 | | | | | | | Savage (1929) and Walls (1935) both reproduce an extract from the parish register for Welford-on-Avon which describes a flood on 18 July 1588 which damaged Clopton Bridge at Stratford-Upon-Avon. The date of the event is thought to be incorrectly recorded, and is the 19 July 1587 event noted in Tewkesbury town records (see Appendix C). The severity of the flood indicates that it is extremely likely that a notable event occurred at Evesham. |
| **3** | 1770 | Nov | 17 | 15.00 | | | | | | Symons (1876) records the 1770 flood as 'The highest flood within memory…probably 15 ft 0 ins', some 3 ins above the 1848 flood. |
| **4** | 1793 | Feb | 10 | | | | | | | Baylis (1985) quotes from the diary of the Vicar of Bengeworth which describes a flood that was said to be within 14 inches of the 1770 flood. |
| **5** | 1799 | Nov | 6 | | | | | | | A local attorney's memorandum book for 1799 describes a flood that reached the Unicorn Inn, Port Street, Bengeworth (Baylis, 1985). |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **6** | 1801 | | | | | | | | | At Stratford both Symons (1876) and the Stratford-Upon-Avon Herald (29 Mar 1867) state that the 1801 flood was higher than that of 1848. The Evesham Standard & West Midland Observer (5 Jan 1901) reports that a flood in the early 1800s [likely to have been that of 1801] was possibly bigger than that of 1848. The Evesham Journal (5 Jan 1901) reports that “there is no doubt that the present flood [31 Dec 1900] flood was higher than that of 1801”. Thus, the 1801 flood is ranked higher than that of 1848 but lower than that of 1900. |
| **7** | 1809 | Feb | | | | | | | | The BHS 'Chronology of British Hydrological Events' provides a quotation taken from the Warwickshire Advertiser of 4 Feb 1809 that describes a notable flood that caused damage to bridges along the Avon and a warehouse at Evesham. |
| **8** | 1821 | Dec | 25 | | | | | | | Symons (1876) gives details of a flood recorded upstream at Stratford-Upon-Avon. Potter (1978) reports that notable flooding did occur in the Midlands. It is likely that a notable event also occurred at Evesham. |
| **9** | 1830 | Jun | 26 | 14.00 | | | | | | |
| **10** | 1848 | Oct | 1 | 14.75 | 15.00 | | 14.25 | 14.25 | 14.38 | |
| **11** | 1852 | Nov | 11 | 14.00 | 14.30 | | 13.50 | 13.50 | 13.68 | Year incorrectly recorded as 1952 by Evesham Journal (16 April 1998). |
| **12** | 1853 | Jul | 10 | | 11.20 | | | 10.42 | | Day of month missing on SRA list. Flood recorded at Stratford on 15th (Symons, 1876). Date for event of 10 July 1853 taken from Evesham Journal (12 Jan 1901) |
| **13** | 1867 | Mar | 24 | | 11.80 | | | 11.04 | | |
| **14** | 1872 | Jan | 24 | | 9.50 | | | 8.75 | | |
| **15** | 1872 | Feb | 20 | | | | | 6.04 | | |
| **16** | 1872 | Nov | 3 | | | | | 7.17 | | |
| **17** | 1872 | Nov | 24 | 8.75 | 10.00 | | | 9.25 | | |
| **18** | 1872 | Nov | 27 | | | | | 7.83 | | |
| **19** | 1872 | Dec | 18 | | 11.60 | | | 10.83 | | |
| **20** | 1875 | Jan | 12 | | 9.30 | | | 8.58 | | |
| **21** | 1875 | Jul | 21 | 12.50 | 12.80 | | 12.04 | 12.04 | | Symons (1876) records this as 22 July 1875. |
| **22** | 1875 | Oct | 10 | 9.50 | | | | 9.08 | | |
| **23** | 1875 | Oct | 12 | | 10.20 | | | 9.42 | | |
| **24** | 1875 | Oct | 21 | 13.10 | 13.40 | | 12.63 | 12.63 | 12.78 | |
| **25** | 1875 | Oct | 28 | 4.50 | | | | 4.50 | | |
| **26** | 1875 | Nov | 7 | 8.50 | 9.30 | | | 8.50 | | |
| **27** | 1875 | Nov | 12 | 10.00 | | | | 9.54 | | |
| **28** | 1875 | Nov | 14 | 12.00 | 12.30 | | | 11.54 | | |
| **29** | 1878 | May | 9 | | | | | 8.33 | | |
| **30** | 1878 | May | 11 | | 10.30 | | | 9.58 | | |
| **31** | 1878 | Nov | 11 | | 9.80 | | | 9.00 | | |
| **32** | 1878 | Dec | 29 | | 9.50 | | | 8.75 | | |
| **33** | 1879 | Jun | 17 | | | | | 5.83 | | |
| **34** | 1879 | Aug | 3 | | | | | 4.75 | | |
| **35** | 1879 | Aug | 17 | | 12.10 | | | 11.33 | | |
| **36** | 1879 | Aug | 20 | | | | | 7.71 | | |
| **37** | 1880 | Feb | 20 | | 9.30 | | | 8.50 | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **38** | 1880 | Jul | 14 | | | 7.25 | | |
| **39** | 1880 | Jul | 17 | 8.90 | | 8.10 | | |
| **40** | 1880 | Sep | 20 | | | 6.00 | | |
| **41** | 1880 | Oct | 6 | 11.30 | | 10.63 | | |
| **42** | 1880 | Nov | 16 | 9.30 | | 8.50 | | |
| **43** | 1880 | Dec | 27 | | | 5.90 | | |
| **44** | 1880 | Dec | 30 | 8.60 | | 7.79 | | |
| **45** | 1881 | Jan | 10 | | | 7.13 | | |
| **46** | 1881 | Feb | 11 | 8.30 | | 7.50 | | |
| **47** | 1881 | Feb | 15 | | | 7.17 | | |
| **48** | 1881 | Dec | 19 | 9.00 | | 8.25 | | |
| **49** | 1882 | Jan | 10 | 8.30 | | 7.54 | | |
| **50** | 1882 | Mar | 1 | 8.20 | | 7.42 | | Evesham Journal (12 Jan 1901) records this as 3 March 1882. |
| **51** | 1882 | Oct | 25 | 13.80 | 13.00 | 13.00 | 13.18 | Evesham Journal (12 Jan 1901) records this as 24 October 1882. |
| **52** | 1882 | Nov | 6 | 9.70 | | 8.92 | | |
| **53** | 1883 | Jan | 30 | 8.10 | | 7.33 | | |
| **54** | 1883 | Feb | 4 | | | 7.33 | | |
| **55** | 1883 | Feb | 11 | 10.50 | | 9.75 | | |
| **56** | 1886 | May | 14 | 12.00 | | 11.25 | | |
| **57** | 1887 | Jan | 11 | | | 7.75 | | |
| **58** | 1887 | Jan | 21 | | | 10.50 | | |
| **59** | 1889 | Mar | 9 | 13.20 | | 12.42 | 12.58 | |
| **60** | 1889 | Apr | 11 | | | 7.33 | | |
| **61** | 1894 | Mar | 15 | 10.00 | | | | |
| **62** | 1894 | Nov | 22 | | | 9.33 | | |
| **63** | 1895 | Jan | 21 | | | 11.00 | | Evesham Journal (12 Jan 1901) lists this event on 21 Jan 1895. The year may be a typographical error since the Severn River Authority list shows a similar event on 21 Jan 1896. |
| **64** | 1895 | Nov | 14 | 8.00 | | | | |
| **65** | 1896 | Jan | 16 | 8.20 | | | | |
| **66** | 1896 | Jan | 21 | 11.90 | | | | |
| **67** | 1897 | Feb | 6 | | | 11.67 | | |
| **68** | 1900 | Feb | 16 | 10.60 | | 9.08 | | Evesham Journal (12 Jan 1901) records this as 17 February 1900. |
| **69** | 1900 | Feb | 20 | | | 9.83 | | |
| **70** | 1900 | Dec | 31 | 15.80 | | 15.00 | 15.18 | Severn River Authority listed the event as 30 December 1990, but Evesham Journal (12 Jan 1901) and Stratford-Upon-Avon Herald (4 Jan 1901) reports that the peak occurred on 31 December 1900. |
| **71** | 1908 | Apr | 29 | 10.70 | | | | |
| **72** | 1910 | Dec | 4 | 10.30 | | | | |
| **73** | 1912 | Jan | 22 | 10.00 | | | | |
| **74** | 1912 | Aug | 27 | 11.20 | | | | |
| **75** | 1914 | Dec | 31 | 11.30 | | | | |
| **76** | 1918 | Jan | 20 | 10.50 | | | | |
| **77** | 1918 | Apr | 22 | 9.00 | | | | |
| **78** | 1920 | Apr | 10 | 10.80 | | | | |
| **79** | 1924 | May | 31 | 13.50 | | | 12.88 | |
| **80** | 1926 | Jan | 2 | 10.20 | | | | |
| **81** | 1928 | Jan | 2 | 9.80 | | | | |
| **82** | 1932 | May | 1 | 11.10 | | | | |
| **83** | 1932 | May | 15 | 9.70 | | | | |
| **84** | 1932 | May | 21 | 13.30 | | | 12.68 | |
| **85** | 1933 | Feb | 24 | 12.20 | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **86** | 1935 | Nov | 18 | 9.00 | | | |
| **87** | 1935 | Dec | 27 | 12.40 | | | |
| **88** | 1939 | Jan | 27 | 10.40 | 227.7 | | |
| **89** | 1939 | Oct | 20 | 9.70 | | | |
| **90** | 1940 | Feb | 8 | 12.60 | 314.4 | | |
| **91** | 1940 | Nov | 22 | 9.30 | 187.2 | | |
| **92** | 1941 | Jan | 23 | 8.70 | 167.4 | | |
| **93** | 1941 | Jan | 26 | 8.40 | 160.0 | | |
| **94** | 1942 | Jan | 25 | 9.20 | 183.5 | | |
| **95** | 1943 | Feb | 1 | 9.70 | 201.9 | | |
| **96** | 1947 | Mar | 14 | 13.50 | 362.5 | 12.88 | |
| **97** | 1947 | Mar | 18 | 11.30 | 257.4 | | |
| **98** | 1950 | Feb | 4 | 8.20 | 154.9 | | |
| **99** | 1950 | Nov | 22 | 8.60 | 166.2 | | |
| **100** | 1951 | Apr | 10 | 8.10 | 153.8 | | |
| **101** | 1955 | Mar | 27 | 9.40 | 190.9 | | |
| **102** | 1955 | May | 18 | 8.80 | 169.4 | | |
| **103** | 1959 | Jan | 7 | 8.80 | 171.1 | | |
| **104** | 1959 | Jan | 18 | 8.40 | 161.1 | | |
| **105** | 1959 | Jan | 23 | 10.80 | 240.7 | | |
| **106** | 1960 | Jan | 25 | 10.80 | 242.4 | | |
| **107** | 1960 | Jan | 29 | 9.80 | 205.6 | | |
| **108** | 1960 | Dec | 4 | 10.10 | 216.6 | | |
| **109** | 1965 | Dec | 10 | 8.10 | 152.4 | | |
| **110** | 1968 | Jan | 14 | 9.50 | 191.7 | | |
| **111** | 1968 | Jul | 12 | 13.50 | 371.0 | 12.88 | Date shown as 11 July 1968 by Evesham Journal (16/4/1998). |
| **112** | 1969 | Mar | 14 | 9.60 | | | |

## Comments

All flood levels are given in feet and the decimal equivalent of the values originally in inches. The flows presented in column $B_2$ are in $m^3s^{-1}$.

The Severn River Authority combined levels taken from Burlingham's record 1937-1969 (flood events 88-112 inclusive) and reduced the levels to the same datum. For convenience the entire dataset (B) is presented here. Information from 1937-1969 does not form part of the historical flood dataset used to review the flood frequency curves (Section 5.7).

For further details regarding the data brought together here, reference should be made to the individual datasets in Appendices A to E.

**APPENDIX G**

**Sources**

A full description of the sources of the data evaluated using the tick boxes below is presented in Appendices A - E. Appendix F brings together all flood information from principal datasets and indicates the source (and relevant Appendix) for data relating to each flood event.

**Data**

| | Where? | | | When? | | | Magnitude? | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Ref.** | River basin | Tributary | Location | Year | Month | Day | Ranking possible? | Level | Flow | Authenticity weighting? |
| **1** | ✓ | ✓ | ✓ | ✓ | | | | | | ✓ |
| **2** | ✓ | ✓ | | | | | | | | |
| **3** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **4** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **5** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓ |
| **6** | ✓ | ✓ | ✓ | ✓ | | | ✓ | | | ✓ |
| **7** | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | ✓ |
| **8** | ✓ | ✓ | | ✓ | ✓ | ✓ | | | | ✓ |
| **9** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **10** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **11** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **12** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **13** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **14** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **15** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **16** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **17** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **18** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **19** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **20** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **21** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **22** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **23** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **24** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **25** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **26** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **27** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **28** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **29** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **30** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **31** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **32** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **33** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **34** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **35** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **36** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **37** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **38** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **39** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **40** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **41** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **42** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **43** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **44** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **45** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **46** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **47** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **48** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **49** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **50** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **51** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **52** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **53** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **54** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **55** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **56** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **57** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **58** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **59** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **60** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **61** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **62** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **63** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **64** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **65** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **66** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **67** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **68** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **69** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **70** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **71** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **72** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **73** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **74** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **75** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **76** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **77** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **78** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **79** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **80** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **81** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **82** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **83** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **84** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **85** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **86** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |
| **87** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓✓ |

## Comments

The historical flood information evaluated here relates to the period 1374 – 1937. The reference number (column 1) is provided as a link to the information being evaluated (Appendix F). Where data relating to an historic event has been collated from more than one source, the authenticity assessment relates to data from the most reliable source.

**APPENDIX H**

**Sources**

The Flood Estimation Handbook flood peak dataset for the period 1937 – 1990 inclusive.

The Highest Instantaneous Flow Series held by the National River Flow Archive CEH Wallingford (supplied by the Environment Agency and its predecessors), for the period 1991 – 1998 inclusive.

**Data**

| Gauge No. | Water Year | Flood date | Peak Flow ($m^3s^{-1}$) |
|---|---|---|---|
| 54002 | 1937 | 13-JAN-1938 | 47.021 |
| 54002 | 1938 | 27-JAN-1939 | 240.382 |
| 54002 | 1939 | 08-FEB-1940 | 316.213 |
| 54002 | 1940 | 22-NOV-1940 | 187.123 |
| 54002 | 1941 | 25-JAN-1942 | 183.657 |
| 54002 | 1942 | 01-FEB-1943 | 201.259 |
| 54002 | 1943 | 24-JAN-1944 | 7.574 |
| 54002 | 1944 | 01-FEB-1945 | 103.298 |
| 54002 | 1945 | 29-DEC-1945 | 86.275 |
| 54002 | 1946 | 14-MAR-1947 | 356.187 |
| 54002 | 1947 | 13-SEP-1948 | 67.11 |
| 54002 | 1948 | 02-JAN-1949 | 91.377 |
| 54002 | 1949 | 04-FEB-1950 | 148.908 |
| 54002 | 1950 | 05-JAN-1951 | 181.934 |
| 54002 | 1951 | 09-NOV-1951 | 130.432 |
| 54002 | 1952 | 21-DEC-1952 | 130.432 |
| 54002 | 1953 | 19-FEB-1954 | 86.275 |
| 54002 | 1954 | 27-MAR-1955 | 190.617 |
| 54002 | 1955 | 31-JAN-1956 | 93.851 |
| 54002 | 1956 | 29-DEC-1956 | 138.782 |
| 54002 | 1957 | 25-FEB-1958 | 137.556 |
| 54002 | 1958 | 22-JAN-1959 | 243.687 |
| 54002 | 1959 | 24-JAN-1960 | 245.633 |
| 54002 | 1960 | 04-DEC-1960 | 215.279 |
| 54002 | 1961 | 07-JAN-1962 | 92.29 |
| 54002 | 1962 | 31-MAR-1963 | 67.913 |
| 54002 | 1963 | 19-NOV-1963 | 117.402 |
| 54002 | 1964 | 21-MAR-1965 | 41.032 |
| 54002 | 1965 | 10-DEC-1965 | 148.443 |
| 54002 | 1966 | 10-MAR-1967 | 131.49 |
| 54002 | 1967 | 11-JUL-1968 | 361.909 |
| 54002 | 1968 | 13-MAR-1969 | 198.944 |
| 54002 | 1969 | 20-FEB-1970 | 94.897 |
| 54002 | 1970 | 24-JAN-1971 | 157.4 |
| 54002 | 1971 | 04-FEB-1972 | 188.904 |
| 54002 | 1972 | 07-DEC-1972 | 112.565 |
| 54002 | 1973 | 11-FEB-1974 | 135.722 |
| 54002 | 1974 | 14-MAR-1975 | 172.612 |

| | | | |
|---|---|---|---|
| 54002 | 1975 | 26-SEP-1976 | 35.937 |
| 54002 | 1976 | 15-JUN-1977 | 176.653 |
| 54002 | 1977 | 28-JAN-1978 | 123.646 |
| 54002 | 1978 | 02-FEB-1979 | 214.387 |
| 54002 | 1979 | 28-DEC-1979 | 230.596 |
| 54002 | 1980 | 11-MAR-1981 | 215.716 |
| 54002 | 1981 | 30-DEC-1981 | 264.091 |
| 54002 | 1982 | 02-MAY-1983 | 155.035 |
| 54002 | 1983 | 07-FEB-1984 | 102.542 |
| 54002 | 1984 | 24-NOV-1984 | 174.533 |
| 54002 | 1985 | 10-JAN-1986 | 145.447 |
| 54002 | 1986 | 05-APR-1987 | 128.578 |
| 54002 | 1987 | 24-JAN-1988 | 192.414 |
| 54002 | 1988 | 07-APR-1989 | 115.592 |
| 54002 | 1989 | 08-FEB-1990 | 163.307 |
| 54002 | 1990 | 10-JAN-1991 | 134.179 |
| 54002 | 1991 | 09-JAN-1992 | 138.800 |
| 54002 | 1992 | 13-JAN-1993 | 212.600 |
| 54002 | 1993 | 05-JAN-1994 | 143.400 |
| 54002 | 1994 | 22-JAN-1995 | 124.300 |
| 54002 | 1995 | 22-DEC-1995 | 113.900 |
| 54002 | 1996 | 26-FEB-1997 | 31.880 |
| 54002 | 1997 | 10-APR-1998 | 427.000 |
| 54002 | 1998 | 16-JAN-1999 | 149.700 |

### Comments

The annual maximum peak flows relate to water years. The water years used here start on 1st October and are labelled by the year in which they begin.