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Wallingford Water

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Upper Ouse Catchment, North Yorkshire

Hydrological and Hydraulic Study

Summary Report

Report EX 3953
December 1998

HR Wallingford

Mr T Andryszewski
Environment Agency North East Region
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File R/R/2406

14 December 1998

Dear Tony

Upper Ouse Catchment, North Yorkshire
Hydrological and Hydraulic Study
Summary Report

Please find enclosed 10 copies of the above report as requested.

This completes the work that you have commissioned us to carry out on this interesting and challenging study. We have enjoyed working with you.

If we can be of further assistance in explaining our findings to the local community please do not hesitate to get in touch with me.

Yours sincerely

Rodney White

Dr W R White
Senior Consultant

Encs

cc. Duncan Reed, IH

Upper Ouse Catchment, North Yorkshire
Hydrological and Hydraulic Study

Summary Report

Report EX 3953
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HR Wallingford

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Contract

This report is the Summary Report for the Upper Ouse Hydrological and Hydraulic Study carried out by HR Wallingford in association with the Institute of Hydrology under their joint venture Wallingford Water. The work was commissioned by Environment Agency, North East Region on 15 December 1997. The EA-NE Region project manager was Mr A Andryszewski and the HR project manager was Dr W Rodney White. Dr Duncan W Reed was responsible for the management of the IH input. The HR job number was RXR 2406.

Contributions to the Main Report were made by Dr Rodney White, Dr Duncan Reed, Mr Rob Millington, Mr Rob Cheetham, Miss Helen Houghton-Carr, Dr Christel Prudhomme, Mrs Doerte Jakob and Mr Adrian Bayliss.

This Summary Report was drafted by Dr W R White.

Prepared by ....

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Date 06.12.98

Summary

Upper Ouse Catchment, North Yorkshire Hydrological and Hydraulic Study

Summary Report

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The upper Ouse river catchment consists of two principal rivers namely the Ure and Swale. The rivers drain the upland region of the north east Pennines in the county of North Yorkshire and channel the water southwards through the Vale of York. The rivers Nidd and Wharfe enter the mid reaches of the Ouse and the Derwent enters the lower reaches. The waters of virtually the whole of North Yorkshire are carried by the Ouse and Derwent eventually leading to the Humber estuary

Many of the towns on the two rivers suffer from flooding, including Catterick Bridge and Catterick on the Swale, and Ripon and Boroughbridge on the Ure. Boroughbridge was flooded in 1968 and 1982 and as a result of the latter event flood defences were constructed. In 1991 further flooding occurred in Boroughbridge when water overtopped part of the flood defences. In 1995 flooding in Boroughbridge was narrowly averted due to raising of part of the defences following the 1991 event.

Following the 1995 flood event the Environment Agency North East Region became concerned that the root cause of the flood risk to Boroughbridge was not fully understood. Furthermore it was felt that any enhancements to the protection works at Boroughbridge would have to be based on a better and more comprehensive understanding of the hydrological and hydraulic factors.

This Wallingford Water study required a comprehensive hydrological and hydraulic assessment to determine, with sufficient confidence, 1) the degree of protection currently provided by the flood defences at Boroughbridge and 2) design defence levels for return periods up to 200 years against flooding from the river Ure.

The Main (Technical) Report, EX 3912, was published in August 1998. This Summary Report focuses on the principal findings of the study and readers should refer to the Main Report, EX 3912, for additional information, if required.

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1. EXECUTIVE SUMMARY

1.1 General

The current project, undertaken by HR Wallingford and the Institute of Hydrology under their joint venture Wallingford Water, included the following aspects:-

- Familiarisation with the historic development of infrastructure in the Upper Ouse catchment.
- Review of previous studies for flood defence schemes.
- Review of recent major flood events.
- Historical review of flooding in the region of Boroughbridge.
- Hydrometric review of the accuracy of river flow data.
- A reassessment of flood flows at Westwick weir.
- Special study of flood volumes.
- Hydrological assessment of flood flow frequencies.
- Hydraulic assessment of flood level frequencies.

At an early stage in the investigation it became clear that the river flow measurements made at Kilgram and Westwick on the Ure and at Crakehill on the Swale were crucial to the accurate prediction of flood flows and levels through Boroughbridge. These gauging stations were therefore carefully examined and, in the light of this, the high flow rating for Westwick was amended.

The hydrological aspects of the project covered the following aspects:

- A review of the four most recent major flood events at Boroughbridge (1968, 1982, 1991 & 1995) was carried out. This included an assessment of the flood hydrographs in the context of antecedent hydrological conditions including rainfall and snowmelt.

- A review of historical flooding at Boroughbridge unearthed information going back to the 16th century. The review helped to compensate for the relatively small sample of recent, well documented, major flood events and put flooding at Boroughbridge into a much longer, and therefore more representative, context.

- Flood frequency analyses, using annual maxima from 1955 to 1996, were carried out using traditional (FSR) techniques as well as methods based on the latest recommendations from the Flood Estimation Handbook (FEH).

- Finally a special analysis of flood volumes was carried out using a method which is widely used in French speaking countries but rarely in the UK. The method is particularly useful where flood plain storage effects are important and where records of flood outlines are available. Both these apply at Boroughbridge. The method, known as the GRADEX method, gives valuable information on flood frequencies and also on appropriate design flood hydrographs.

The final output from the hydrological work was flood frequency and design hydrograph information. This was then used in the ISIS hydraulic model to simulate flow and water level conditions through Boroughbridge for a range of flood events with return periods from 5 to 200 years.

The final task was to compare flood levels through Boroughbridge with the levels of the existing defences. This gave information on the standard of protection provided by the current flood defence embankments at Boroughbridge and determined the extent to which the defences would have to be upgraded if a higher standard were considered appropriate and economically justifiable.

1.2 Main findings

The main findings of this project are summarised as follows:-

1.2.1 Boroughbridge has a long history of flooding. The review of historical flooding showed major events spread throughout the 19th century, an absence of major events in the first 60 years of the 20th century and four major events in the last 30 years.

1.2.2 The principal flood risk at Boroughbridge arises from the Ure. Prior to construction of the diversion scheme in 1987, the town generally experienced the flood effect of the Ure via the Tutt.

1.2.3 The Ure is sensitive to prolonged heavy rainfall, usually of 2 to 3 days duration. Snowmelt is an important contributor to many of the larger floods.

1.2.4 The flood behaviour of the Ure is relatively unusual. Floodplain storage along the Ure, both natural and in the Ings (i.e. designated washlands), is important in moderating peak flows and water levels.

1.2.5 Because of these storage effects, there is concern about Boroughbridge's sensitivity to major floods of long duration, such as occurred in January 1883 and January 1982.

1.2.6 High flows at Westwick, and therefore through Boroughbridge, had previously been overestimated. Best estimates for the maximum flows at Westwick in recent floods are as follows:-

1968: 408 m^3s^{-1}
1982: 462 m^3s^{-1}
1991: 516 m^3s^{-1}
1995: 518 m^3s^{-1}

1.2.7 Flood frequencies for Boroughbridge, based on Westwick flows, are:-

5 year return period:	340 m^3s^{-1}
10 year return period:	388 m^3s^{-1}
20 year return period:	439 m^3s^{-1}
50 year return period:	512 m^3s^{-1}
100 year return period:	574 m^3s^{-1}
200 year return period:	644 m^3s^{-1}

1.2.8 Assuming a ***design level*** 300 mm below ***current defence levels*** the current protection provided for Boroughbridge is an event which may occur, on average, once every 35 years i.e. there is an annual risk of the ***design levels*** being exceeded of 0.029.

1.2.9 Assuming a ***design level*** 300 mm below ***current defence levels*** at Boroughbridge, flood levels relative to the ***design level*** at the critical location 123 m upstream of the road bridge for a range of return periods are as follows:-

5 year return period:	0.76 m ***below*** design level
10 year return period:	0.44 m ***below*** design level
20 year return period:	0.13 m ***below*** design level
50 year return period:	0.08 m ***above*** design level
100 year return period:	0.28 m ***above*** design level
200 year return period:	0.47 m ***above*** design level

1.2.10 The event which ***overtops*** the Boroughbridge defences is an event which may occur once every 110 years ie there is an annual risk of 0.009.

1.2.11 Relative to ***current defence levels*** at Boroughbridge (critical location 123 m upstream of Boroughbridge road bridge), flood levels for a range of return periods are as follows:-

5 year return period:	1.06 m ***below*** defence level
10 year return period:	0.74 m ***below*** defence level
20 year return period:	0.43 m ***below*** defence level
50 year return period:	0.22 m ***below*** defence level
100 year return period:	0.02 m ***below*** defence level
200 year return period:	0.17 m ***above*** defence level

The above water levels relative to ***current defence levels*** assume that no spill into Boroughbridge is permitted to take place ie for the 200 year return period event the modelling has assumed that the defences would be raised to contain flows within the river. Without such raising Boroughbridge would act as a spill area in the very rare events and this has not been simulated

1.2.12 In studying the causes of flooding in Boroughbridge, the following have been ruled out as having no significant effect:-

- Tide levels in the Humber
- Backing up caused by the flood defences at York
- Backing up caused by flood defence works at Lower Dunsforth
- Backing up caused by floods in the river Swale

1.2.13 Previous activities which have affected flood levels to a variable extent over a long period of time, both at Boroughbridge and throughout the Ouse catchment include:-

- Development of villages and towns in the floodplain (including Boroughbridge!)
- The development of the Ings system
- The construction of flood defences
- Gradual changes in agricultural practices - and hence the vegetation cover in the catchment

1.2.14 Factors which may slowly change the flood characteristics in the future, both at Boroughbridge and throughout the Ouse catchment, include:-

- Further man-made interventions
- Climate change

1.2.15 Snowmelt has been an important contributory factor in about half of the largest Ure floods noted in the last 200 years. It is unclear whether global warming will increase the frequency of flooding in Boroughbridge.

2. BACKGROUND AND INTRODUCTION

2.1 Location

The upper Ouse river catchment consists of two principal rivers namely the Ure and Swale. The rivers drain the upland region of the north east Pennines in the county of North Yorkshire and channel the water southwards through the Vale of York. The rivers Nidd and Wharfe enter the mid reaches of the Ouse and the Derwent enters the lower reaches. The waters of virtually the whole of North Yorkshire are carried by the Ouse and Derwent eventually leading to the Humber estuary. Figure 2.1 shows the Dales Area plan.

2.2 History of flooding

Many of the towns on the two rivers suffer from flooding, including Catterick Bridge and Catterick on the Swale, and Ripon and Boroughbridge on the Ure.

Boroughbridge has a long history of flooding, well documented in recent times. Boroughbridge was flooded in 1968 and 1982 and as a result of the latter event flood defences were constructed. In 1991 further flooding occurred in Boroughbridge and on this occasion overtopped part of the flood defences. In 1995 flooding in Boroughbridge was prevented due to raising of part of the defences following the 1991 event.

2.3 Catchment

The Ure and the Swale are the principal rivers in the Upper Ouse catchment. The rivers rise in the upland region of the Pennines about 50 km WNW of Boroughbridge, fall through the Yorkshire Dales towards the Vale of York, and join approximately 5 km E of Boroughbridge. Having subsumed the Swale, the Ure changes its name to the Ouse a further 8 km downstream. The Tutt rises some 7 km SW of Boroughbridge, and flowing NE into the town where it joins the Ure.

The Ure rises in the Pennines at an altitude of around 672 m AOD, and falls some 650 m in elevation, to the gauging station at Westwick Weir (catchment area 915 km^2), which is about 5.5 km upstream of Boroughbridge. Most tributaries of the Ure, including the Tutt, join on its right bank. In its upper reaches the Ure catchment is steep and the geology is mainly Carboniferous limestone. Further downstream, Millstone Grit forms gentle hills, whilst towards the downstream extent Magnesian Limestone and Permian Marls form a level plain. The Ure is predominantly rural, with Ripon the most significant urban area. Average annual rainfall exceeds 2000 mm in much of the upper catchment of the Ure, where snow cover is common during winter months.

The Swale catchment is similar topographically to the Ure, rising in the Pennines at an altitude of around 710 m AOD, and falling, some 560 m in elevation, to the gauging station at Crakehill (catchment area 1363 km^2), which is about 11.5 km upstream of the confluence with the Ure. The geology is mainly limestones, sandstones and shales with a covering of boulder clay. The Swale is also predominantly rural, with its upper catchment having a high average annual rainfall and frequent winter snow cover.

The Tutt catchment (area 39.8 km^2) is situated in the lowlands between Knaresborough and Boroughbridge. Being a lowland catchment, the Tutt experiences generally lower annual rainfall totals and less frequent and extensive snow cover than do the adjacent uplands. With an average annual rainfall of about 650 mm, the regime is similar to that of lowland Britain. It has a tendency towards large summer rainfalls, as opposed to the more even balance between summer and winter rainfalls in upland areas. The Tutt catchment is of very gentle relief, extending SW from its confluence with the Ure to its watershed with tributary catchments to the Nidd. Elevation ranges between 10 and 74 m AOD. It is essentially a small rural area, mostly given over to mixed agriculture and pasture with small areas of woods and parklands. A few small villages lie within the catchment, as well as Boroughbridge itself. There are considerable numbers of ponds and evidence of artificial drainage and straightening of some reaches in the upper catchment. These phenomena suggest poor natural drainage with potential for waterlogging.

The Agency has many sites in the catchment to record rainfall, river level and flow. The location and type of gauging are included in Figure 2.2. Information from all the sites can be remotely accessed.

2.4 Flooding

Following heavy rainfall and/or snowmelt the rivers Ure and Swale rise causing flooding at many locations which may include Richmond and Catterick Bridge on the Swale, and Ripon, Boroughbridge and Lower Dunsforth on the Ure.

In recent times significant flood events have occurred in 1968, 1982, 1991 and 1995. It was the 1982 event which prompted the construction of flood defences in the Boroughbridge area, then built to an intended design standard of 1 in 100 years return period.

The 1991 event overtopped part of the Boroughbridge defences and as a result part of the defences were raised. In addition the neighbouring villages of Milby, Lower Dunsforth and Roecliffe were flooded and also Richmond and Catterick Bridge on the Swale. The 1991 event was the highest flood level recorded on the Ure at Boroughbridge since 1883 and was classed as a freak event at the time.

In 1995 the levels of the Ure and Swale again rose and flooded many properties. The defences at Boroughbridge were effective but the peak river level came close to overtopping. The villages of Milby, Roecliffe and Lower Dunsforth were less fortunate with many houses, roads and commercial properties flooded. The 1995 peak flow was of similar magnitude to that of 1991 and flooding to undefended properties was inevitable.

2.5 Previous Studies

Many previous studies have been carried out and these are discussed in detail in the Main Report, EX3912. These studies were aimed specifically at providing 1) financial justification for the construction of flood defences in the Upper Ouse catchment and 2) design information for these defences. The studies were mainly based on recent hydrological information, typically from 1960 onwards, and involved various statistical analyses of flooding. They were not aimed at providing an understanding of the detailed hydrological and hydraulic characteristics of the catchment.

3. STUDY BRIEF

The brief for the current study was to undertake a comprehensive hydrological and hydraulic study to understand better the causes of flooding in the Upper Ouse catchment and to determine defence levels, for the town of Boroughbridge, for return periods up to 200 years against flooding from the river Ure.

The Agency, and formerly the NRA, have examined the defences at Boroughbridge since the 1991 event but to date no improvement works have been undertaken because of doubts in the hydrology and hydraulics. The Agency commissioned this study to allay these doubts and to provide sound proposals based on the best information and expertise currently available.

The detailed Terms of Reference for this study are given in Appendix 1 of the Main Report, EX 3912.

4. FLOOD ESTIMATION

4.1 Introduction

This chapter describes (Section 4.2) the factors which have to be taken into account in assessing flood risk and then discusses flow measurement (Section 4.3) at three crucial flow gauging stations on the Ure and the Swale. There follows a review of the four most recent major flood events (Section 4.4) and an assessment of the salient factors which contributed to their magnitude. In contrast to this detailed look at recent events there follows an overview of historical flooding at Boroughbridge (Section 4.5) dating back to the 16^{th} century and placing flooding at Boroughbridge in a much broader context.

The hydrological and hydraulic analyses carried out as part of the study are summarised in Sections 4.6 to 4.9 inclusive. These lead to the main conclusions concerning frequencies of flood flows and flood levels for Boroughbridge.

Further details of historic flooding are given in the Appendix.

4.2 Flood risk at Boroughbridge

Flood risk assessment for Boroughbridge Town is not simple. There are many complications: some natural, others man-made.

4.2.1 Natural factors

There are three natural complicating factors: (1) the catchment is relatively permeable, (2) the Ure has substantial floodplains along much of its lower course and (3) the town lies at the Tutt/Ure confluence. The last factor means that flood risk at Boroughbridge Town is largely, but not solely, determined by Ure flows.

Substantial natural floodplains are good news in a flood defence context, since the temporary storage of water in flood meadows reduces the magnitude of the flood peak that would otherwise be experienced downstream. But rivers with extensive floodplains pose a difficulty for flood risk assessment because the floodplain may itself be overwhelmed in the very largest floods, and defended floodplains (see Section 4.2.2) present a further complication. Thus observed behaviour in medium to large flood events may not be a good guide to behaviour in the very largest floods.

An additional complicating factor is that the catchment is susceptible to snowmelt flooding. This reflects the size and topography of the catchment, and the climatology of north-east England. But it also reflects the permeability of the soils. Major floods on small impermeable catchments tend to arise from heavy rainfall alone. But large catchments can be vulnerable to snowmelt floods, because rapid melting of snow in unison over a large portion of the catchment can more readily yield runoff rates comparable to that from heavy rainfall.

4.2.2 Man-made factors

Concerns have been expressed that changes in land use – such as urbanization, moorland drainage, and intensive sheep-rearing – may have increased flood frequency at Boroughbridge. However, the more significant complications are those arising from flood defence activities. There are three flood defence components that impinge on flood risk at Boroughbridge Town.

Embankments at Boroughbridge

The town is protected against flooding from the Ure by flood embankments, walls and gates. Notable improvements were made after the 1982 flood and (to a lesser extent) after the February 1991 event.

In the main, these are riverside flood defences. However, the Aldborough cross-bank east of the town, and (informally) the A1 bypass embankment west of the town, are important in separating the natural floodplain cell on which the town lies from its downstream and upstream neighbours. As constructed in about 1986, it transpired that the Aldborough cross-bank was too low to fulfil this role in major floods. It was reconstructed to a higher level following the February 1991 flood. Prior to construction of the A1 bypass, the upstream cut-off was provided by the embankment of the Knaresborough to Boroughbridge branch railway, constructed around 1875.

Tutt component of the flood defence scheme

The second flood defence component influencing flood risk at Boroughbridge Town is the Tutt scheme. It is evident that in January 1982, and earlier major floods, water entered the town via the Tutt, as a consequence of high water levels in the Ure preventing the Tutt from freely discharging. Water level data for the January 1982 flood suggest that reverse flow took place from the Ure to the Tutt. The Tutt scheme was designed to eliminate this.

In some respects, the Tutt scheme simplifies the flood risk assessment problem for Boroughbridge Town. This is because the design of the scheme provides for the town to be at a very much smaller risk of flooding from the Tutt than from the Ure, effectively eliminating the Tutt as an important consideration in itself. As a consequence, this project can concentrate on assessing the flood risk to Boroughbridge Town posed by the combined catchments of the Ure and Tutt.

Other flood embankments

Further flood embankments affecting flood risks at Boroughbridge Town are washland embankments upstream of the town. These embankments are set at a level which optimises the use of flood plain storage and assists in reducing flood risks to properties downstream.

The use of such embankments has been employed for many decades and is recognised as an effective means of river management for flood alleviation.

4.3 River flow measurement

It has not been possible in this study to look in detail at all the flow gauging stations in the Upper Ouse catchment. However, the importance, in relation to the flood risks at Boroughbridge, of the three gauging stations at Kilgram and Westwick on the Ure and Crakehill on the Swale has been recognised and the three stations have been looked at in some detail.

Kilgram, R. Ure

The station at Kilgram is a current meter (CM) rating station with cableway. It was installed in 1967 and has not been altered since that date. Velocities are recorded using current meters suspended from the cableway and levels on a chart recorder. There is also a series of gauge boards at the site for manual observation of water levels. The site is not outflanked during flood events.

The reach of the Ure at Kilgram is stable. The bridge some 70 m downstream exerts some control on levels and helps to maintain a unique stage/discharge relationship at the CM station.

This site is an excellent site for a CM gauging station and the gauging results show little scatter. The rating curve is smooth and there is no evidence that the rating has changed since 1971. The differences between the 1967 – 1971 and the 1971 – 1997 ratings are small and are not significant in terms of the present study which is concerned with extreme events. The HYDROLOG rating curve shows good agreement with the observed flows.

Westwick, R. Ure

Historical information about this site has been difficult to obtain and some of the evidence is contradictory. We understand that the current meter rating station with cableway was installed in 1957 at its present location some 250 m downstream of Westwick weir and that it has been in continuous use since that date. Prior to 1975, stage was measured some 50 metres downstream of the cableway close to the downstream end of the lock cut.

In 1970 Westwick weir was renovated by British Waterways Board. An internal memorandum of the Yorkshire Water Authority states that Boroughbridge weir was also renovated in 1970. To take advantage of the newly renovated Westwick weir, and the stable control of water level which this provides, stage has been measured upstream of the Westwick weir from 1975 onwards.

The current meter rating appears consistent and the individual gaugings produce a continuous smooth curve with little scatter up to around 250 m3/s. The HYDROLOG rating curve for this station is valid from 1975 and shows good agreement with the observed flows

The Westwick rating for high flows has been questioned in previous studies relating to Boroughbridge. For this reason and because of the uncertainties listed above the rating for high flows was re-assessed as part of this study.

Revised rating:

The revised Westwick rating is based on a detailed hydraulic assessment of flow conditions throughout the reach through Boroughbridge covered by the ISIS model. The analysis is purely hydraulic and does not prejudice any hydrological considerations.

The work has produced a revised rating for Westwick weir at stage levels in excess of 2.0m (250 m^3/s) which deviates from the EA rating and high flows are reduced significantly by the revised rating. Details are given in the Main Report EX 3912.

Crakehill, R. Swale

Prior to 1980 flows were measured using the current meter rating station at Leckby Grange. However, accuracy at low flows was not good and access to the site was proving to be difficult. In 1980 a Crump weir was built a short distance downstream at Crakehill. Since that date, stage has been measured at the Crump weir and discharges continue to be measured at Leckby Grange.

The Crump weir becomes drowned before water levels reach wing wall level. When observed on 6 January 1998 the head over the weir was 1.62 m and water levels were close to wing wall levels. The weir was heavily drowned.

The rating for the station is based on the CM discharge figures although some attempt has been made to compare these results with standard weir equations at low flows. The weir is thus acting as a control rather than a measuring device which was probably not the original intention.

Assuming systematic errors are small, we conclude that, as far as extreme floods are concerned, the flows indicated at Crakehill have only a reasonable accuracy. This station does not give the quality of results now available at Kilgram and Westwick.

4.4 Review of recent major floods

Four major flood events have occurred on the Ure in the last 30 years: in March 1968, January 1982, February 1991 and February 1995. In each case, damage was extensive, involving overtopping or breaching of floodbanks, inundation of farmland and urban areas, and disruption to transport links, utilities and communications. However, in February 1995, the flood defences prevented the inundation of Boroughbridge town. These four events are reviewed from a hydrological viewpoint in Appendix 2 of the Main Report, EX

3912. This section summarises the findings of the review, drawing out the key features of the events, and their similarities and differences. The findings are presented in terms of the relevance and contribution of the antecedent conditions and the various flood-promoting processes, such as rainfall and snowmelt.

4.4.1 Flow hydrographs

Figure 4.1 compares the flow hydrographs from the four events for the Ure at both Kilgram and Westwick and the Swale at Crakehill. The hydrographs reveal that the Swale responds very differently to the Ure. The flow hydrographs at Leckby/Crakehill have a strongly attenuated (flat topped) appearance compared to the corresponding Kilgram and Westwick hydrographs and, though the volume of the hydrographs varies considerably between events, the recorded peaks are consistently around 225 m^3s^{-1}.

4.4.2 Comparison of events

The 1968 event was caused primarily by heavy rainfall with little, if any, snowmelt. The Ure rose steadily over 24 to 36 hours, and the high water level at the peak caused the Tutt to back up and flood Boroughbridge.

The 1982 event was caused by heavy rainfall coupled with considerable snowmelt. The Ure rose steadily over 24 to 36 hours, and overtopped, and subsequently breached, its banks at two locations causing flooding in Boroughbridge and Milby; the high water level in the Ure at the peak caused the Tutt to back up and contribute to the flood in Boroughbridge. The Ure took about 72 hours to fall to pre-event levels.

The 1991 event was caused primarily by heavy rainfall with only a small, probably insignificant, snowmelt contribution. The Ure rose steadily over 24 to 36 hours, and overtopped its banks causing flooding in Milby, Roecliffe and Langthorpe, and filling the Aldborough Ings; the overtopping of the Aldborough Ings cross-bank led to the flooding in Boroughbridge.

The 1995 event was caused by heavy rainfall coupled with snowmelt. The Ure rose steadily over 12 to 24 hours, overtopped its banks causing flooding in Milby and Langthorpe; Boroughbridge, with the benefits of improvements to its flood defences following the 1991 event, was not seriously flooded.

4.5 Historical review of flooding at Boroughbridge

The recent major floods reviewed above are of prime importance in assessing flood risk at Boroughbridge. However it is also helpful to investigate flooding in earlier years. The Appendix to this report presents a detailed review of the flood history at Boroughbridge, with particular emphasis on floods prior to October 1955, when formal flow gauging commenced at Westwick.

The historical review strengthens the judgement of flood frequency by:

- Compensating for the (statistically) small sample of gauged flood flows;
- Allowing the recent flood experience to be put in a longer-term context;
- Uncovering forgotten information about Boroughbridge floods.

The Appendix interprets the historical information in various ways, commenting on Swale floods, climate change, land-use effects, embankments and islands. The principal findings relevant to the assessment of flood frequency at Boroughbridge are:

- Floods at Boroughbridge and York are statistically interdependent, although flooding at York cannot cause flooding at Boroughbridge. Some events give rise to major flooding at both places (e.g. 1982 and 1991); some yield a major flood only at Boroughbridge (e.g. 1822, 1883 and 1995); while others yield a major flood only at York (e.g. 1831 and 1947);
- The most severe floods are predisposed to occur in the winter half-year, October to March. Half of the most severe floods at Boroughbridge have occurred within seven days of 3rd February;
- Snowmelt is a contributing factor in more than half of major floods at Boroughbridge, and an important factor in at least half of the largest floods (notably: 1881, 1883 and 1982);

- Many of the high-impact floods derive from rainfall, or rain and snowmelt, *of long duration* (e.g. 1822, 1883 and 1982).

The depth of information gathered is sufficient to warrant detailed interpretation. The review draws up a tentative ranking of the 12 largest floods experienced in the last 200 years (Figure 4.2). The ranking is based on the inferred *impact* of flooding. This explains why the (long-duration) 1991 event is ranked above the (short-duration) 1995 event, despite having a slightly smaller gauged peak flow at Westwick.

The irregular pattern of occurrence of major floods (Figure 4.2) makes it difficult to assign return periods to the highest impact floods of 1883 and 1991. However, it is suggested that the March 1968 flood can be considered to approximate a 20-year event, being about the 10^{th} most severe flood at Boroughbridge in 200 years.

4.6 Flood frequency analysis for the river Ure at Westwick

4.6.1 Approaches

The approaches used in the flood frequency analysis encompassed a well established UK technique (The Flood Studies Report), a new UK technique which is based on recent research for MAFF (The Flood Estimation Handbook) and a technique developed overseas but which is of particular relevance to rivers with extensive flood plain storage (The French GRADEX/AGREGEE method).

Details of these methods and how they were applied to the flooding characteristics of the Upper Ouse are given in the Main Report, EX 3912.

4.6.2 Recommended flood frequency estimates, Ure at Westwick

The flood frequency estimates, in terms of peak flows, are summarised in Table 4.1. The recommended estimates (in bold) are those based on a particular method given in the Flood Estimation Handbook. The detailed reasoning behind this particular choice is given in the Main Report, EX 3912.

Because of the extensive gauged and historical data at Boroughbridge, and the lack of strong differences between "rainfall only" and "rainfall plus snowmelt" events on the Ure, there is no particular case for considering a joint probability analysis. Such studies are difficult and give scope for misconstruction. They are best reserved for cases where two distinct (and distinguishable) factors operate to produce flooding.

Table 4.1 T-year peak flow estimates (m^3s^{-1}), Ure at Westwick

Return period years	Flood Studies Report (GEV distribution)	**Flood Estimation Handbook (GLO distribution)**	GRADEX AGREGEE method
5	347	**340**	323
10	397	**388**	368
20	445	**439**	424
50	506	**512**	521
100	551	**574**	609
200	596	**644**	705

4.7 Analysis of flood volumes

Experience suggested at the outset that Boroughbridge is particularly sensitive to floods of long duration. This is evident both in the types of event that have given rise to major flooding, and in the associated extensive inundation of floodplains alongside the Ure as a prelude to major flooding in the town. Consequently, a special analysis of flood volumes was included in the study brief.

Application of the AGREGEE method was undertaken in this study, see Main Report EX 3912 for details. The method used information on flood storage in the Upper Ouse basin and also the records available which show inundated areas in historic floods. The outcome was a set of basic flood hydrographs.

4.8 Design hydrographs

The set of basic hydrographs described in Section 4.7 were modified to take into account various factors before producing the design flood hydrographs for the Ure at Westwick as shown in Figure 4.3.

Flood hydrographs on the Swale typically exhibit a sustained peak, which is broadly concurrent with the Ure hydrograph peak (see Figure 4.1).

4.9 Flood levels at Boroughbridge

The ISIS model was used to simulate flow conditions through Boroughbridge for a range of flood frequencies in the river Ure. Quoted flows are those at Westwick but a small amount of additional flow was input to the model downstream of Westwick. Two per cent of Westick flows were assumed to be generated by the Tutt and a further two per cent by the rest of the catchment between Westwick and the Swale confluence.

A summary of the tests undertaken is given in Table 4.2. Ure floods were simulated for a range of return periods from 5 years to 200 years. In all these tests the river Swale flows were derived by taking the 1991 flood as approximately a 50 year event and thereafter deriving other return period flows by analogy with the Ure. Additionally, sensitivity tests were carried out at the 50 year event to see the influence of lower or higher flows in the river Swale, see Main Report EX 3912 for details.

In all the simulations no spill was permitted into Boroughbridge ie for the highest floods it was assumed that the flood walls were high enough to prevent inundation of the town.

Table 4.2 Final simulations of the Boroughbridge reach

Test No.	River Ure		River Swale
	Return Period	Peak Flow (m^3/s)	Peak Flow (m^3/s)
1	5	340 (=0.66 Q_{50yr})	149 (=0.66 Q_{1991})
2	10	388 (=0.76 Q_{50yr})	171 (=0.76 Q_{1991})
3	20	439 (=0.86 Q_{50yr})	193 (=0.86 Q_{1991})
4	50	512	225 (Q_{1991})
5	50	512	248 (=1.1 Q_{1991})
6	50	512	203 (=0.9 Q_{1991})
7	100	574 (=1.12 Q_{50yr})	252 (=1.12 Q_{1991})
8	200	644 (=1.26 Q_{50yr})	283 (=1.26 Q_{1991})

Flood defence levels (top of the wall) surrounding Boroughbridge are almost constant. The level of the wall on the right bank immediately upstream of the road bridge is recorded as 15.96 mAD. Downstream of the road bridge the recorded level is 15.93 mAD. Following the 1991 flood event the downstream embankment across Aldborough Ings was raised to match the rest of the defences. The level of the Aldborough Ings embankment is 16.20 mAD, well above foreseeable flood levels.

The critical location from a flooding point of view is upstream of Boroughbridge road bridge because head losses caused by the bridge inevitably make water levels upstream higher than those downstream relative to defence level. Simulated flood levels at the critical location 123 m upstream of the road bridge where the wall level is 15.93 mAD are given in Table 4.3. The results are presented firstly in relation to the top of the defences and secondly in relation to design levels which assume a freeboard of 300 mm.

Table 4.3 Flood levels relative to the current defences at Boroughbridge

Test No.	**River Ure Return Period (yrs)**	**Flood level 123 m upstream of road bridge (mAD)**	**Flood level relative to defence level, 15.93 mAD (m)**	**Flood level relative to design level, 15.63 mAD i.e. 300 mm freeboard (m)**
1	5	14.87	-1.06	-0.76
2	10	15.19	-0.74	-0.44
3	20	15.50	-0.43	-0.13
4	50	15.71	-0.22	+0.08
5	50	15.71	-0.22	+0.08
6	50	15.71	-0.22	+0.08
7	100	15.91	-0.02	+0.28
8	200	16.10	+0.17	+0.47

Current level of protection at Boroughbridge

The flood level / frequency relationship given in Table 4.3 can be expressed, with sufficient accuracy between return periods of 20 and 200 years, by the relationship:-

$$L = 13.97 + R^{0.143}$$

[L is the flood level in mAD, 123m upstream of the road bridge, and R is the return period of the flood in years]

Substitution of the freeboard elevation of 15.63 mAD gives a return period of 35 years. The current defences at Boroughbridge are deemed to provide this degree of protection.

Substitution of the elevation of the top of the defences of 15.93 mAD gives a return period of 110 years. This is the frequency at which water would spill into Boroughbridge, initially over the wall upstream of Boroughbridge road bridge.

Longitudinal water surface profiles for the Boroughbridge reach, at peak flow conditions, are given in Figure 4.4 which shows the results for 5, 10, 20, 50, 100 and 200 year return periods. The plot shows maximum water surface profiles and Boroughbridge defence levels.

Head losses through Boroughbridge road bridge

The road bridge causes head losses which are significant during major floods. Water levels upstream of the bridge are significantly higher than those downstream, particularly during major flood events.

Details are given in the Main Report, EX 3912.

5. CONCLUSIONS AND RECOMMENDATIONS

General conclusions

5.1 This study has concentrated on the hydrology of the upper Ouse catchment and the hydraulics of flood flows in the vicinity of Boroughbridge. The study commenced with a familiarisation exercise to establish the availability of hydrological and hydraulic data, the nature and findings of previous studies and the history of the development of the flood defences for Boroughbridge and neighbouring towns and villages. A hydrometric study was carried out to establish the availability and accuracy of river flow measurements. This led to a re-assessment of the Westwick flow gauge. The hydrological study looked generally at historical flooding around Boroughbridge and in detail at the last 30 years of flow records including the 1968, 1982, 1991 and 1995 flood events. The final outcome from the hydrological study was flood flow / frequency information and hydrographs for design events. The hydraulic study took the output from the hydrological study and provided, using the ISIS numerical model, flood level / frequency information. This confirmed the level of protection provided by the current defences of Boroughbridge and the increase in levels which would be required for more secure defences.

5.2 The three key river gauging stations are at Kilgram and Westwick on the Ure and at Crakehill on the Swale. The Kilgram gauge provides excellent records from 1967 onwards. The Westwick gauge has had a chequered history. Prior to 1975 the results obtained from this station were only of moderate quality. In 1975, however, the weir at Westwick was rebuilt and water levels were measured upstream of the weir. This provided some improvement in the flow record. Doubts about the high flow rating still applied because of the complex flow patterns which occur once the river exceeds bank full level. This problem was addressed in the current study and improvements were made. The flow gauging station at Crakehill combines a low Crump weir with a current meter station further upstream. There are uncertainties in the measured flows at the extremes of the flow range. Because of these uncertainties sensitivity tests were carried out to determine the effects of any inaccuracies in Swale flows on flood levels in Boroughbridge.

5.3 The historical review of flooding in and around Boroughbridge gave information going back to the 16^{th} century. The twelve highest impact floods were dated and this showed serious events spread throughout the 19^{th} century, an absence of major events in the first 60 years of the 20^{th} century and four major events in the last 30 years. This review put the recent major flood events of 1991 and 1995 into a longer time context.

5.4 The detailed review of the 1968, 1982, 1991 and 1995 events looked at the flow hydrographs and the factors which can affect the run-off characteristics of a catchment including antecedent conditions, rainfall and snowmelt. The catchment was found to be susceptible to long duration events of 48 to 72 hours and snowmelt was found to be an important factor in some, but not all, of the recent major floods.

5.5 The flood frequency analysis for Boroughbridge used several methods including the Flood Studies Report (FSR) and Flood Estimation Handbook (FEH) statistical methods. Additionally we used the GRADEX / AGREGEE method which has been shown to be of great value where flood storage effects are significant. The method also provided useful information on the most appropriate shape for design flood hydrographs.

5.6 The hydraulic study provided flood level / frequency information for Boroughbridge. This showed that the current design standard of the Boroughbridge defences is for a 35 year event.

5.7 Several possible causes of flooding in Boroughbridge had previously been suggested by the public. We ruled out the following : tide levels in the Humber, backing up caused by the flood defences at York and backing up caused the works at Lower Dunsforth amongst others.

Recommendations

5.8 Within the timeframe and budget for this study we had to be selective in terms of the number of issues which were followed up and the depth of investigation of each. There are two particular aspects of the hydrology which would further improve confidence in flood level predictions for Boroughbridge. First would be to do a full hydrological study of the Swale to check the assumption made in this study that the Swale and the Ure are statistically similar from a flooding point of view. Second would be to carry out a thorough investigation of the Westwick flow rating prior to 1975 in order to further improve the value of flood frequency analyses based upon the output from this gauge.

5.9 The logical next step is to carry out a design study to look at the engineering possibilities for improved flood protection for Boroughbridge and the economic justification for providing a higher standard of protection.

5.10 Engineering studies should consider raising bank/wall levels, bridge improvements, modifications to the river channel and flood attenuation using off-line storage. These items should be hydraulically modelled and the modelling should include sensitivity analyses to evaluate possible uncertainties in those factors which may affect flood levels.

6. REFERENCE

Wallingford Water. 1998. Upper Ouse Catchment, North Yorkshire: Hydrological and Hydraulic Study. Report EX 3912.

Figures

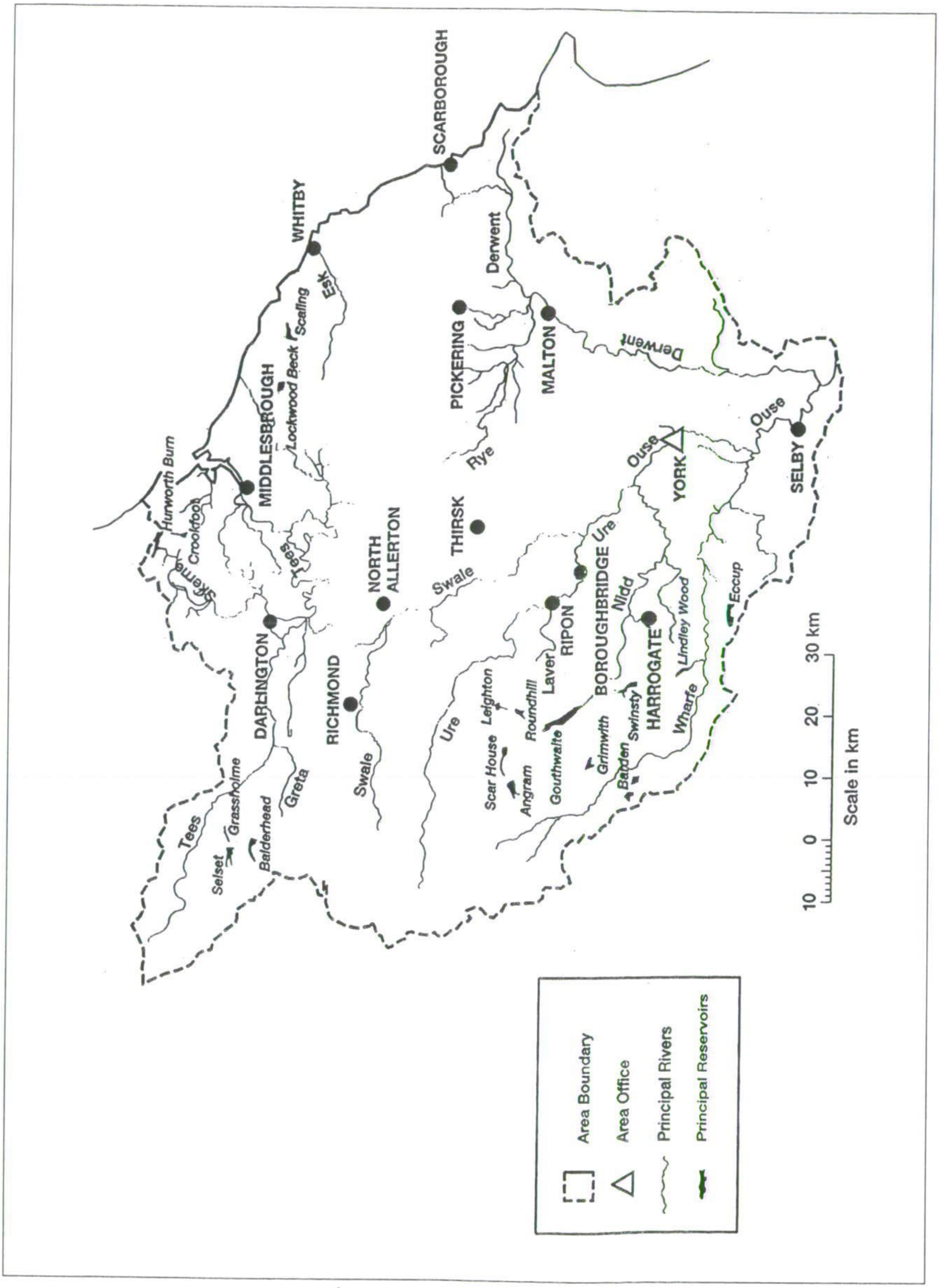

Figure 2.1 Dales Area Plan

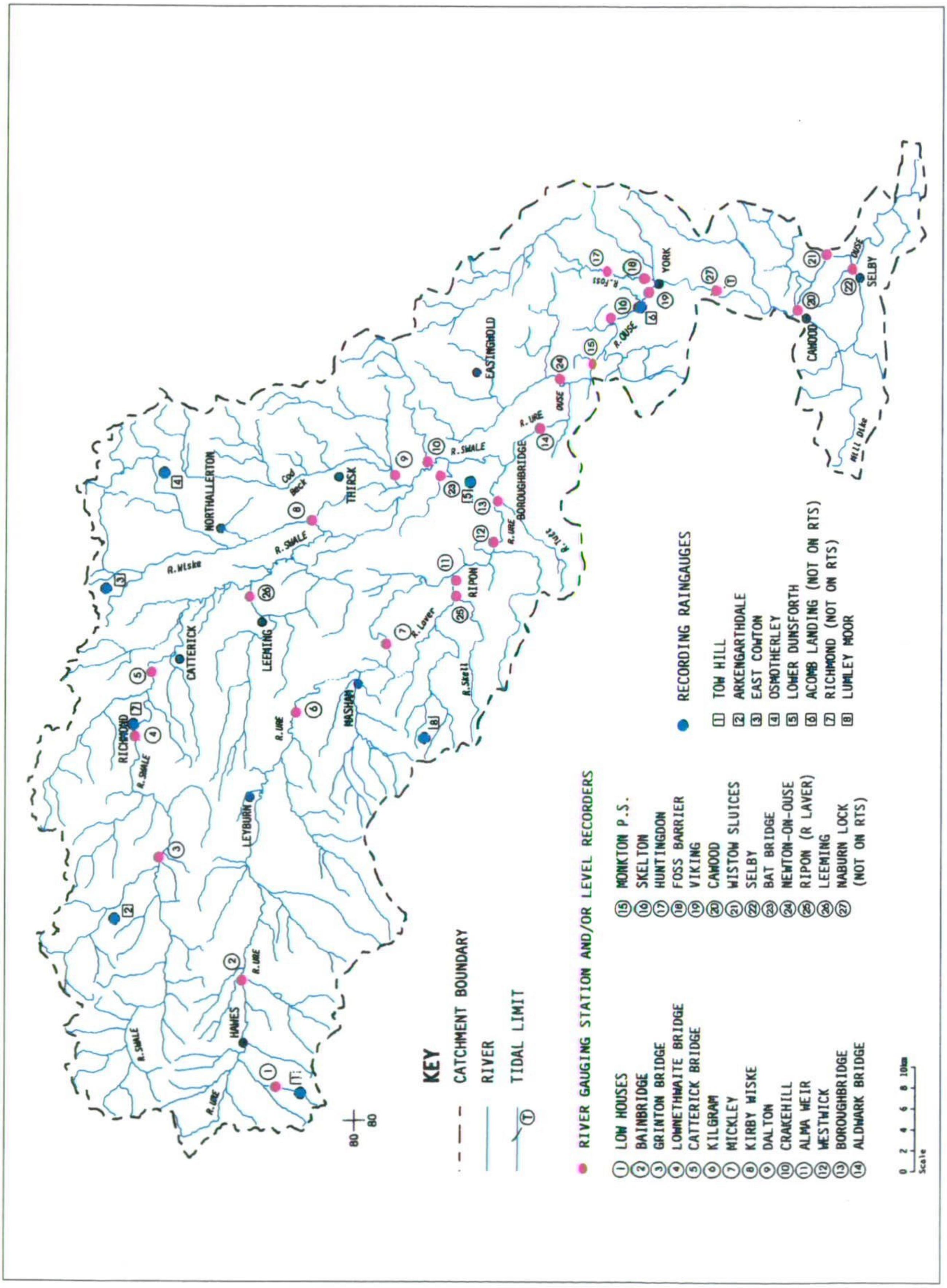

Figure 2.2 Swale, Ure and Ouse Area, River and Rainfall Gauging Stations

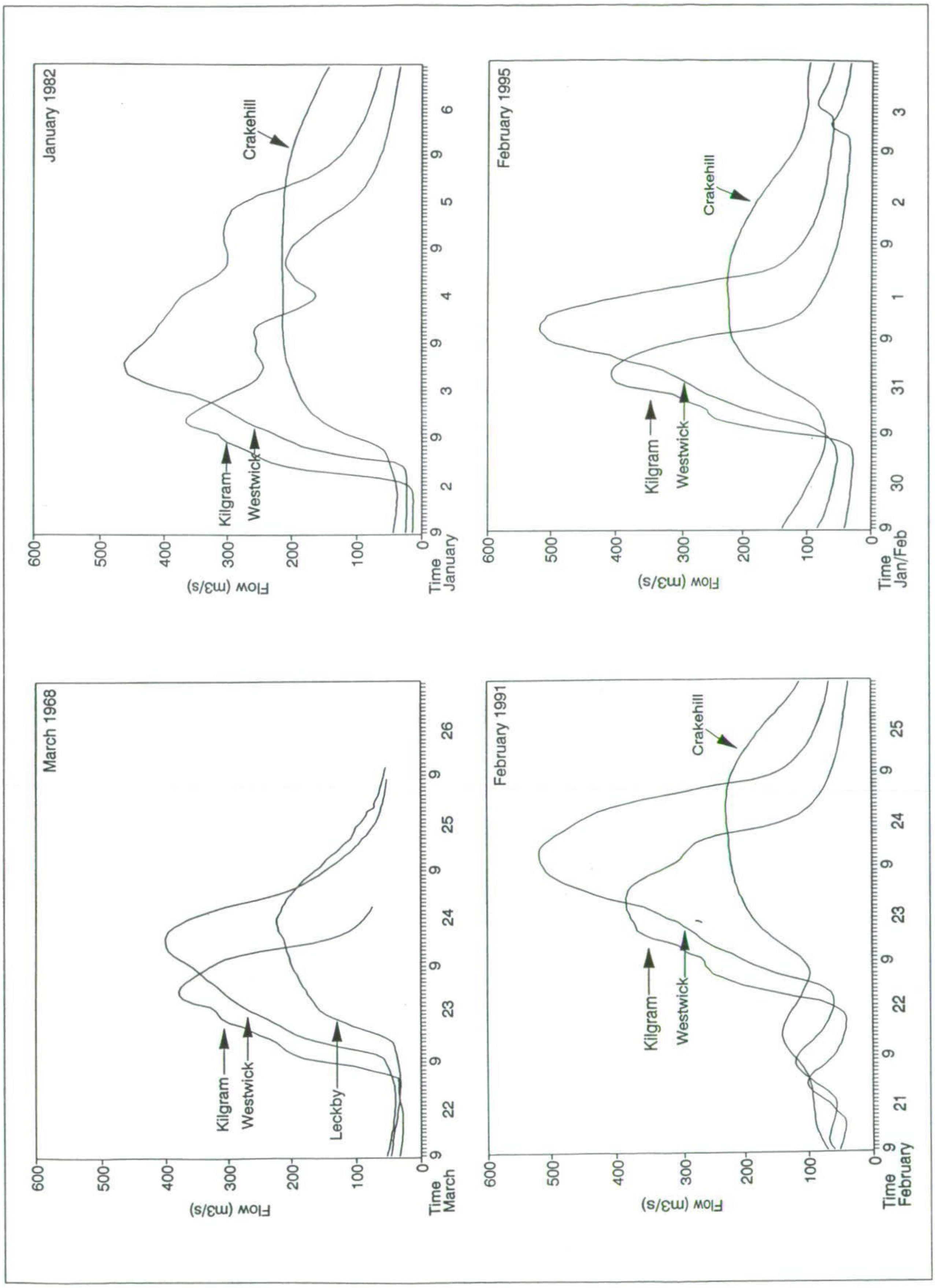

Figure 4.1 Ure and Swale hydrographs for 1968, 1982, 1991 and 1995 events

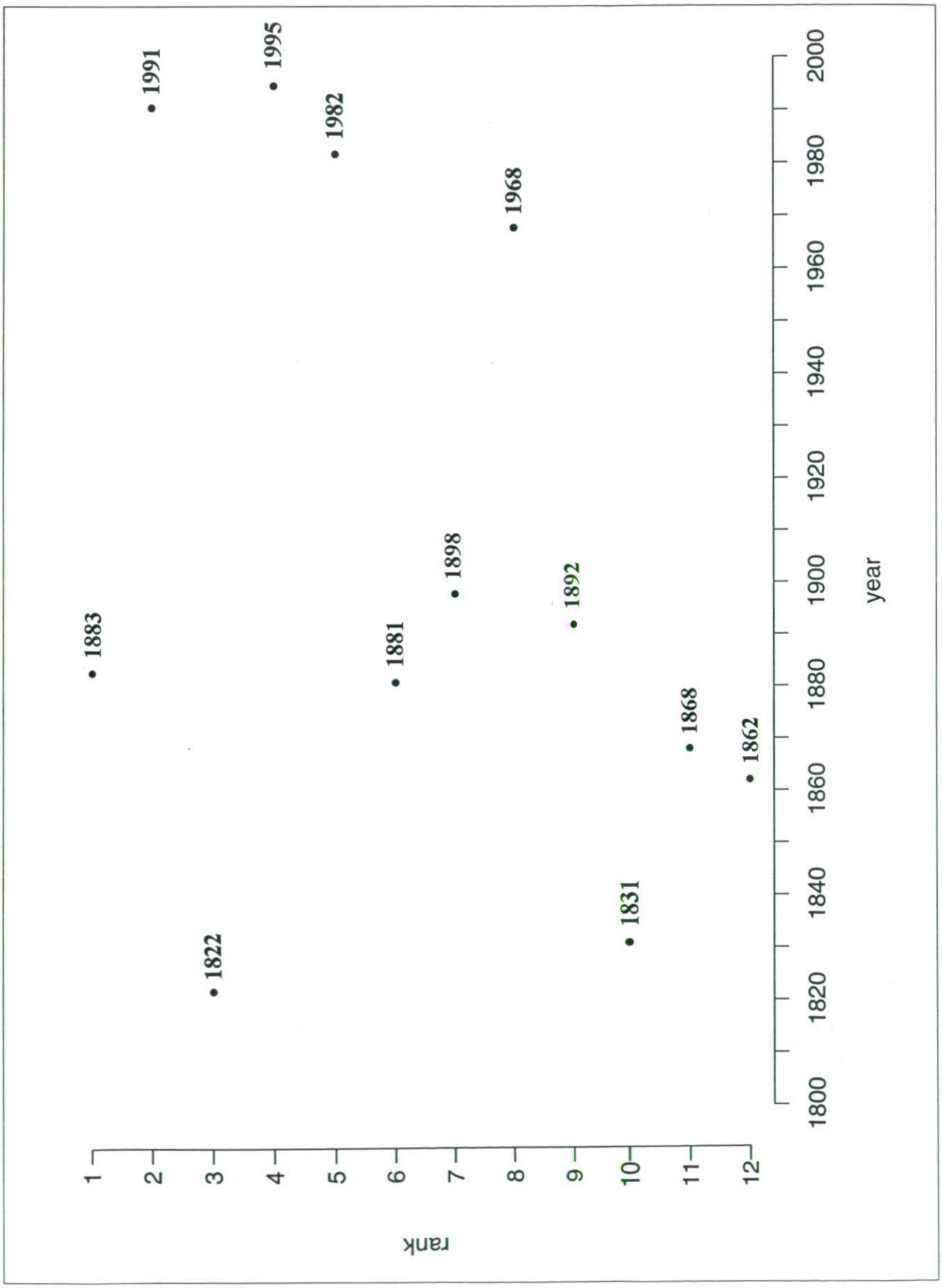

Figure 4.2 Tentative ranking of 12 largest Ure floods in 200 years (1798-1997)

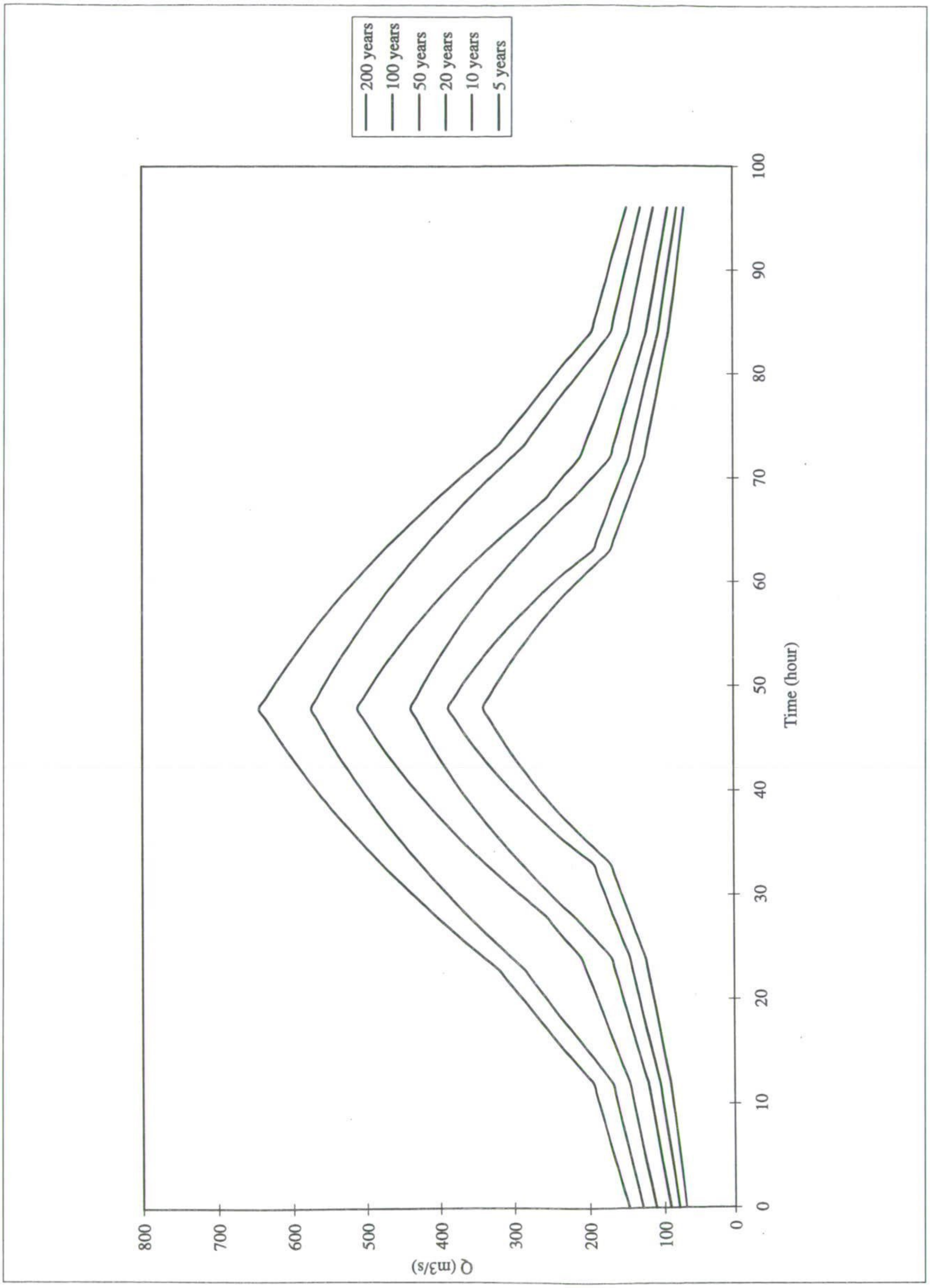

Figure 4.3 Design hydrographs

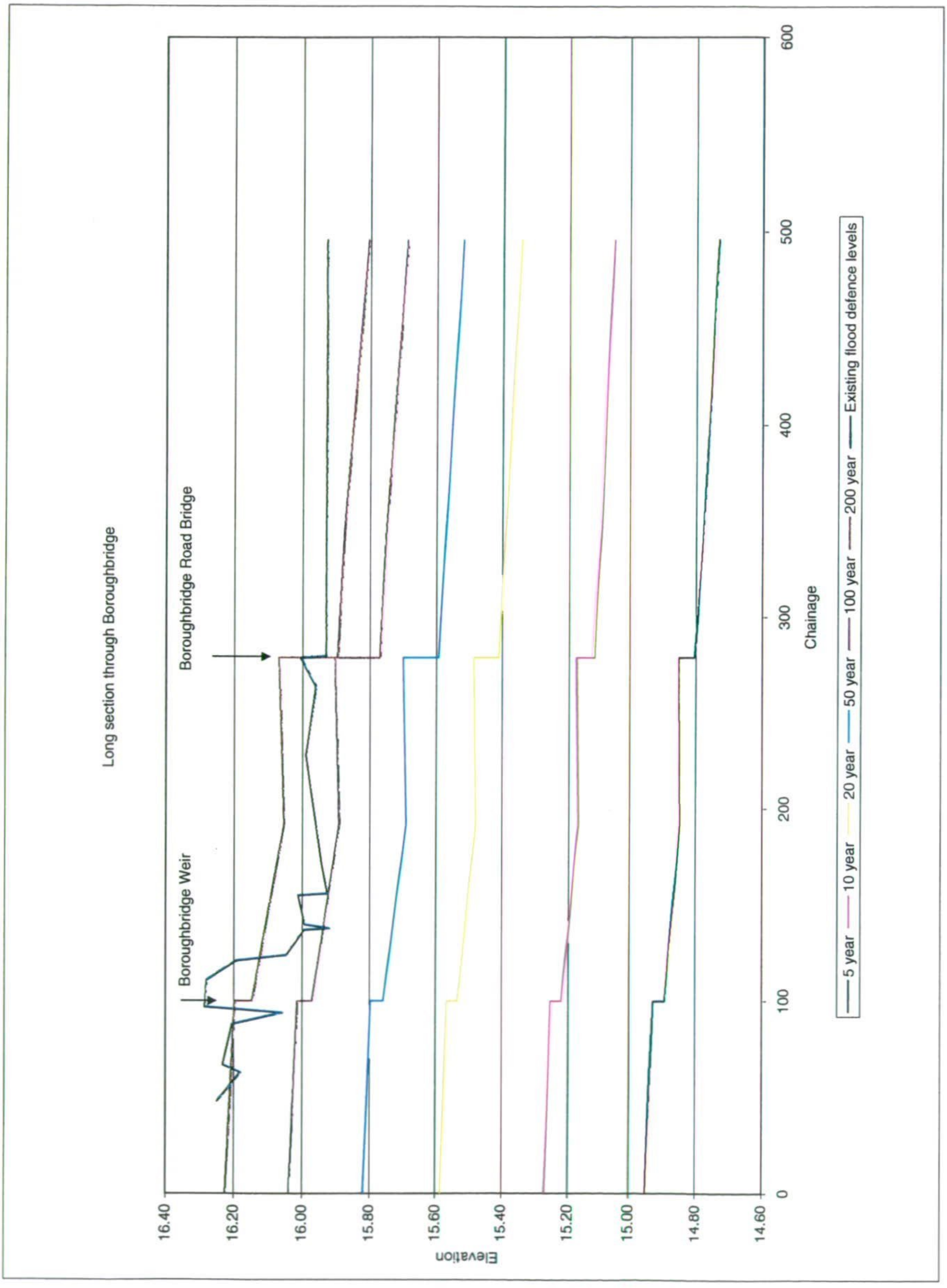

Figure 4.4 Boroughbridge reach: water surface profiles

Appendix

Appendix 1

Review of historical flooding at Boroughbridge

Appendix 1 Review of historical flooding at Boroughbridge

A1 Why carry out a historical review?

Formal gauging of the river Ure began in 1955, with flow measurement at Westwick Weir approx. 6 km upstream of Boroughbridge. This means that the statistical analysis of floods is based on 42 years of record.

There are several reasons why it is helpful to augment the analysis by examining evidence of floods prior to 1955. The study calls for estimation of the magnitude of infrequent floods: for example, the so-called 100-year flood. This has a probability of only 0.01 of being exceeded in any year. Such a flood is not certain to have occurred within the gauged period. *On average*, the probability of experiencing the 100-year flood at least once within a 42-year period is:

$$p = 1 - (1 - 1/100)^{42} = 0.34$$

Thus the statistical analysis is trying to estimate an event that may not have been experienced during the period of gauged record.

The flood that has an even chance of being experienced within a 42-year period is the 61-year flood, for which:

$$1 - (1 - 1/61)^{42} = 0.50.$$

It is important to think clearly when using the term "return period". There is no regularity in flood occurrences. A very long period may elapse without an extreme event occurring. The occurrence of an extreme flood does not make a further extreme flood any more or less likely to occur; it may, however, lead to a change in perceptions and estimates of the flood risk.

A small sample

Attention focuses on the largest floods for which flows have been gauged: March 1968, January 1982, February 1991 and February 1995. These floods were large enough to have a significant general impact on Boroughbridge. Deductions about the 100-year flood inevitably place emphasis on the peak flows recorded in these four floods. Yet four numbers represent a very small sample. If we wanted to know the average height of Boroughbridge residents, we would not be confident that averaging the height of the first four people we met would provide a good estimate: it might but it might not. Thus the first reason why a historical review is helpful is that the gauged sample of major floods is very small.

An unusual sample?

The sequence of floods is such that it is possible to think that there may be an element of misfortune in experiencing two major floods within a 4-year period (February 1991 and February 1995). Another view is that there might be some factor leading to major floods becoming more frequent; drainage works and climate change are amongst the factors mentioned. A historical review can help to put the recent flood experience into a longer-term perspective.

Uncovering forgotten information

Any historical review is inevitably incomplete. However, uncovering forgotten information adds credibility and contributes to public understanding, in addition to putting the statistical analysis of Ure floods into a longer-term perspective.

A2 Sources

Some historical information about floods is given in earlier studies of the flooding problem at Boroughbridge: in particular, the January 1983 draft report by MMP. Various additional sources of information have been explored, including:

Searches of documents held in public libraries (Boroughbridge and Ripon),

Inspection of newspaper records (Ripon Gazette, Ripon, and Ackrill Newspaper Group, Harrogate) for dates for which floods were suspected, Miscellaneous publications, including *British Rainfall* and others suggested by Potter (1978).

The process of historical review is inevitably messy: like trying to do a jigsaw for which pieces are missing, others damaged, and some belong to a different puzzle. To keep subjectivity to a minimum, and facilitate checks, the sources of historical information are indicated.

A3 Chronology of Ure floods

This review pieces together historical information about flooding at Boroughbridge from about the last 400 years. Some dates not directly relating to flooding are included as points of reference, mainly in the early period. Dates in bold correspond to specific flood events, although not all of these are known to have been significant at Boroughbridge. Dates in brackets refer to documents or meetings.

1557
Boroughbridge became a Borough. [Baines, 1822]

1564-65
Great flood after a sudden thaw carried away Ouse Bridge at York, where there was an ice jam. [Radley and Simms, 1970; British Rainfall, 1892] Nothing known specifically for Boroughbridge.

<1582
Stone bridge at Boroughbridge predates at least 1582. [Swain, 1893]

March 1614
Major flood at York. Thaw in 1614 devastated large areas (around York) when the flood remained at its height for ten days. [British Rainfall, 1892; Radley and Simms, 1970] Nothing known for Boroughbridge.

February 1625
Highest recorded water level at Ouse Bridge, York. [British Rainfall, 1892; Radley and Simms, 1970; NERC, 1975] Nothing known specifically for Boroughbridge.

1636
Second highest recorded flood at Ouse Bridge, York. [NERC (1975) puts it first equal with 1625; Radley and Simms (1970) put it second] Nothing known specifically for Boroughbridge.

October 1689
Major flood at York. [British Rainfall, 1892] Nothing known specifically for Boroughbridge.

2 February 1732/33
[This date is c 11 February 1733 under Gregorian Calendar]
Masham and Tanfield bridges "broken down" by Ure flood; North bridge at Ripon "greatly damaged" [Fisher, 1865] Flood records at Ouse Bridge in York indicate a major flood in January 1732 (presumably 1732/33) [British Rainfall, 1892] This may have been the largest 18th century flood at Boroughbridge.

1752
Year in which Gregorian Calendar took over from Julian Calendar and counting years relative to Lady Day (25 March) ceased.

26 December 1763
Flood at York. [British Rainfall, 1892] Nothing known specifically for Boroughbridge but Yorkshire Water Authority (1980) states "December 1763; Ure/Ouse; Heavy snowfall; Long duration flooding" without confirming source.

1766-71

Construction of canal (inc. Westwick Weir, Milby Cut and Boroughbridge Weir. Was there an earlier weir at Boroughbridge?) "When Smeaton surveyed the River Ure in 1766 there was an island in the river at the bend below Westwick, and various shoals at Roecliffe." Smeaton proposed a lock and dam at Redbank but they cleared the shoals instead. "The floods of the winter 1770/71 washed a gap thirty yards wide and eight feet deep in Westwick Dam." Smeaton visited on 14 May 1771. Because Redbank was never built, and because of the consequent limited draught, they had to "raise the height of his dam [presumably Boroughbridge Weir] by timbers secured to its crest. The successors to those timbers still top that dam." [Ripon Motor Boat Club, 1986]

November 1771

Exceptionally severe flood on Tyne and Tees. Nothing known specifically for Boroughbridge but Yorkshire Water Authority (1980) states "1771; Swale/Ure; Greatest flood for many centuries" without confirming source.

16 October 1789

First London-Edinburgh mail coach came through Boroughbridge [Dalesman, 1964]

[1792]

"On raising the banks to prevent floods at this place [i.e. Boroughbridge] in the year 1792, a great number of human bones ... were found a little below the bridge." [Baines, 1822] "In 1792 many bones, pieces of armour and arms were brought to light on the river banks." [Hebden, 1971]

1795

Flood at York. [British Rainfall, 1892] Nothing known specifically for Boroughbridge.

2 February 1822

Bridge at Masham (built 1754) was "nearly swept away by the great flood of the 2nd of February, 1822, which did very great damage, not only to the foundations of the bridge, but to the country generally." "... a very great flood of the River Yore ... caused great destruction to a vast amount of property." [Fisher, 1865] "The river is sometimes subject to floods, the waters rushing down with velocity when no rain has fallen in this neighbourhood. The greatest in living memory was in the month of February, 1822, when the water rushed over the banks and overspread the country to a great extent; the town of Boroughbridge was inundated from the bridge to the old Church [i.e. St James Square], so that boats were rowed in the streets. This continued for some days, the water standing three or four feet deep in many of the houses; no lives were lost, but considerable damage was done to property, and years elapsed before the flooded houses were cleared of the dampness caused by this irruption." [Whellan and Sheahan, 1871, quoting from Turner's *History of Aldborough and Boroughbridge*] "The river is sometimes subject to floods, and the town, which lies low, is occasionally inundated. One of these took place in February, 1822, when the water stood from three to four feet deep in many of the houses, doing considerable damage to property. But a still greater flood occurred on the 29th January, 1883 ..." [Bulmer, 1891] "In 1822, the town was submerged to a depth of several feet ... but no record of the actual height to which the water reached was preserved. In 1883 a similar catastrophe befell the inhabitants ..." [Swain, 1893] Not a noted flood at York but there were quickly rising floods in Leeds and Bradford on 3 February. [p. 229 of Vol. 1 of Schroeder, 1851]. Yorkshire Water Authority (1980) states "February 1822; Swale/Ouse; Highest recorded levels at Topcliffe" without confirming source.

10 February 1831

Major flood at York. Nothing known for Boroughbridge. Yorkshire Water Authority (1980) states "1831; Ouse; Frost followed by snow and rain" without confirming source. Archer (1992) states, for 9 February 1831, that the Ouse suffered a severe snowmelt flood accompanied by strong south-westerly winds.

1834-36

River seriously dredged from York to Boroughbridge. [pp. 319-319 of Vol. 1 of Schroeder, 1851] Level of river raised 18 inches between Naburn and Linton by construction of innovative self-acting wasteboard on

Naburn weir [Minutes of Proc. ICE, 24 February 1840, Vol. 1, 26-27] Combined effect of measures said to have reduced height of winter floods.

mid-19th century
"The long terrace of houses on this left side running up to the Black Bull Inn was built after 1850 and replaced a row of very old property there which suffered severely during the frequent floods. In Mr. Clarke's iron yard at the opposite side and to the west of the little bridge, there was a row of five small one-storey-only cottages named Victoria Cottages, which were frequently made uninhabitable during floods and I can remember seeing Canon Owen once carry an old widow out of one of these cottages on his back, during a flood." Owen was Curate in 1850. [John Smith, c. 1953] Owen was a Reverend in 1883. [Topham, c. 1930]

[1855]
Aldborough Ings named on map.

3 February 1862
Flood mark at Mickley Weir. [Sansom, 1996] Building only has two flood marks [?]; hence, ranking relative to other floods unclear. Nothing known specifically for Boroughbridge, but see 1868 entry. British Rainfall (1862) has insufficient information.

[c. 1863]
Mr C. Clarke read paper no. 4 to the Boroughbridge Agricultural Society on *Land draining*.

1 February 1868
Flood mark at Mickley Weir [Sansom, 1996] Building only has two flood marks [?]; hence, ranking relative to other floods unclear. Nothing known specifically for Boroughbridge. However, British Rainfall (1868) indicates heavy rainfall on 30 and 31 January, and gales and widespread floods on 1 February. Also Radley and Simms (1970) label February 1868 as an important flood specifically affecting the Ure. This corroborates 1868 as a noteworthy flood and, by implication, that the February 1862 flood may also have been. These floods may be the mid 19th-century floods referred to by Smith (see above). Yorkshire Water Authority (1980) states "February 1868; Ure; High levels recorded" without confirming source.

1875
Knaresborough to Boroughbridge branch railway opened, crossing the Ure (embankment and bridge, approx. 500 m upstream of Borough Bridge).

[1 January 1881]
Mr A.D.H. Leadman of Boroughbridge read paper no. 72 to the Boroughbridge Agricultural Society on *The prevention of floods*. Copy not found but newspaper report refers to Airedale deluge in 1866 which caused damage exceeding £1m [going some for 1866] and a flood in July 1872 of the "Valley of the Don" in which 15000 acres were flooded. The author recommended (for general practice) that flood embankments be constructed 200 yards from the river on either side. The discussion raised maintenance/migration issues of such a policy, and referred to a House of Lords Select Committee report of 1877. The discussion, and possibly Leadman's paper, appeared to dwell mainly on the protection of agricultural land. [Ripon Gazette and Observer, 6 January 1881]

10 March 1881
"The thaw and west wind have brought the rivers down in a flood. At Burnfoot, where the Burn and Yore join, the place is like a lake ..." Deep snow in Masham beforehand. 6ft snowdrifts elsewhere. Many weeks of bad conditions previously. Bad snowstorm at Moorcock Inn on 3rd March. "A more severe season on the moors has not been experienced within the memory of man." "Early on Wednesday [9th] a rapid thaw set in, accompanied by a downpour of rain. The snow melted quickly, causing all the brooks and rivers to overflow their banks. During the night the Swale burst its banks at Great Langton ... 400 yards of [railway] embankment carried away [between Ainderby and Scruton stations]". [Bedale and Northallerton Times, 12

March 1881] Rainfall observer at Darlington noted "heavy snow storm on 5th, followed by rapid thaw, causing tremendous flood in the Tees from 8th to 10th." [British Rainfall, 1881]

29 January 1883
"The town and neighbourhood of Boroughbridge have been visited by one of the most severe floods which have taken place for many years. On Monday afternoon the rivers Ure and Tutt rose very rapidly ... when, without any warning, the county wall adjoining the river Tutt gave way." "The sudden rush of water took many of the townspeople by surprise ..." "The water reached the height of 17 feet above its usual level." "The water has reached houses that no living person can remember to have flooded before." [Topham, c. 1930] "But a still greater flood [than February 1822] occurred on the 29th January, 1883; the streets were submerged for some days, the water rising to the height of sixty-one and a half inches at the Police Station. On this occasion the bridge over the Tut, built by Blind Jack of Knaresborough [i.e. John Metcalf], was washed down." [Bulmer, 1891] "The Police Station in New Row was not built until 1905." Police station used to be in Hall Square (*aka* Market Square). "This locality [Hall Square] is the very lowest part of Boroughbridge and always suffered severely in frequent floods and it is recorded that in January 1883 flood water was 61½ inches deep at the Police Station in the square." A National Relief Fund raised over £3000. "The little Fishergate bridge over the Beck was built by Blind Jack of Knaresborough in 1754 — the north wall gave way in the great flood of 1883 and so gave relief to the town." [Smith, c. 1953] "In 1883 a similar [to 1822] catastrophe befell the inhabitants, the water rising to a height of five feet in some of the houses in the lower part of the town. The Tut beck ... was on this latter occasion [i.e. 1883] so swollen that the bridge which crosses it in Fishergate burst on the north side, and the great blocks of stone of which it was constructed by Blind Jack of Knaresborough were carried a considerable distance by the strength of the current." [Swain, 1893] British Rainfall (1882) reports "Great snowstorm, said to be the worst for 20 years" at East Layton (near Darlington) on 6 December 1882, and low temperatures through latter part of month at various sites, after "very wet autumn" at Aysgarth. British Rainfall (1883) confirms snow, heavy rainfall, gales and floods in region 27-29 January 1883, with Skipton and Bedale reporting particularly severe floods.

[c. 1885]
Mr A.D.H. Leadman read paper no. 86 to the Boroughbridge Agricultural Society on *Is legislation for the prevention of floods necessary?*

25 January 1890
Heavy flood in Swaledale. [British Rainfall, 1892] Nothing known specifically for Boroughbridge.

15/16 October 1892
Houses flooded in many Yorkshire towns, including Boroughbridge. Isohyetal map (see Figure A.1) shows that largest 3-day rainfall depths were experienced in headwaters of Ure. [British Rainfall, 1892, p.115] Reporting flood levels at York — highest since 1831 — the City Engineer commented: "The improved system of draining now adopted for agricultural land, and the greater extent of land under drainage as compared with 60 years ago, leads me to believe that floods are likely to be more frequent and severe than formerly, although they are not likely to be of such long duration." [Creer, 1892]

c. 18 October 1898?
Flood chronology given in MMP draft report (January 1983) gives an inundation map for the 1898 flood but does not quote full date. Source document (YWA, 1982) not seen but entries in British Rainfall (1898) suggest causal storm was on 17 October. Severity of rainfall uncertain from sketchy data seen. "There have been floods in the town since that date [referring to 1883], the most severe being at the end of the last century — but these never reached the height or caused anything like the damage done by the one recorded above." [Topham, c. 1930] This seems to confirm that floods occurred in both 1892 and 1898, and that the 1898 flood had the greater impact at Boroughbridge.

c. 13 November 1901
3.02 inches in 19 hours, starting 9 pm on 11th. Ure flood followed a notable drought. Some damage. [Harrogate Advertiser, 16 November 1901] Nothing known specifically for Boroughbridge.

[1909]
25" to 1 mile map of Boroughbridge (Figure A2) shows:
- spot-heights and benchmarks,
- embankments on west and east banks of Tutt downstream of Fishergate (and for part of the way between Fishergate and St Helena),
- an embankment east of Boroughbridge Hall,
- five islands between the weir and Borough Bridge,
- flood defences along the Ure between the weir and the Tutt outfall.

Apart from the mill, the map shows no property north of Mill Lane. A photograph, taken in "early years of [20th] century", shows the islands. [Ripon Motor Boat Club, 1986]

[1910]
6" to 1 mile map of Boroughbridge and district (Figure A3) shows:
- Knaresborough and Boroughbridge branch railway,
- Land "liable to floods" on the banks opposite Roecliffe and Langthorpe
- Land "liable to floods" alongside the Tutt upstream of Boroughbridge
- An embankment along south side of Ure from Boroughbridge to Hall Arm Lane (assuming continuity across small sections north and east of that appearing on Fig. A3.3) largely defining Aldborough Ings.

>1917
"Peat and humus-rich soils act as a sponge, absorbing rainfall and slowly releasing it into streams, but its run-off retarding function can be reduced, partly by the considerable erosion of the peat in some areas, partly by the fact that this material has only a limited capacity to absorb rainfall and partly by the extensive gripping (cutting of drains) of the peat which commenced after World War I and is still being extended to speed up run-off." [Radley and Simms, 1970, speaking about headwater catchments in Yorkshire generally]

c. 15 December 1936?
Flood in 1936 quoted by MMP draft report (January 1983) but full date not given. Source document (YWA, 1982) not seen but entries in British Rainfall (1936) suggest causal storm was on 13 December.

c. 23 March 1947
Ure and Skell in full spate but water depths at Ripon did not reach record heights. [Ripon Gazette and Observer, 27 March 1947] Major flood at York (Foss related?) MMP draft report (1983) indicates minor flooding at Boroughbridge.

1957
Knaresborough to Boroughbridge branch railway closed. (Any important changes to embankment subsequently?)

23 March 1968
"Flood havoc worst this century" Ure stopped rising a few inches short of 1883 plaque on North Bridge, Ripon. 5.39 inches in just over 24 hours near Hawes. Rain came after a fall of snow. [Ripon Gazette and Observer, 29 March 1968] Important flood at Boroughbridge - see Section 4.4.

2 July 1968
Ripon experienced violent storm, leading to extensive local flooding — but not at Boroughbridge.

December 1978
Flood in York (Foss related?) No flood at Boroughbridge.

4 January 1982
"The worst flood in memory" [Ripon Gazette and Observer, 8 January 1982] Major flood at Boroughbridge - see Section 4.4.

24 February 1991
Major flood at Boroughbridge - see Section 4.4.

2 February 1995
Major flood at Boroughbridge - see Section 4.4.

A4 Tentative ranking of floods

Based on the above historical information, the following ranking of floods at Boroughbridge is suggested. Little information was found to allow the 1831, 1862, 1868, 1881, 1892 and 1898 floods to be ranked with confidence. The March 1968 is shown as being smaller than the 1881 and 1898 events but larger than the 1831, 1862, 1868 and 1892 floods. Earlier floods, and their significance, are more easily overlooked, and it is possible that additional floods were more severe than the 1968 event. To reflect this uncertainty, the preferred estimate is that the 1968 flood was the 10th largest in 200 years.

Table A1 Largest floods at Boroughbridge, 1798-1997

Rank	Year	Day	Duration	Snowmelt contribution?	Flood at York?	Remarks
1	1883	29 Jan	Long	Major	No	
2	1991	24 Feb	Medium	Minor	Major	
3	1822	2 Feb	Long	?	Yes	
4	1995	2 Feb	Short	Yes	No	
5	1982	4 Jan	Long	Major	Major	
6	1881	10 Mar	Medium?	Major	Yes	
7	1898	18 Oct?	?	No	?	
8*	1968	23 Mar	Medium	Minor	Major	4 days after another flood
9	1892	16 Oct	Medium	No	Major	
10	1831	10 Feb	?	Yes	Major	
11	1868	1 Feb	?	Yes?	No	
12	1862	3 Feb	?	?	?	Heavy snow on 19 Jan?

*See text about preferred estimate of rank of 1968 flood.

The most singular feature of the historical flood series at Boroughbridge (see Figure 4.2) is the absence of major floods in the 70 years between 1898 and 1968 events. The reports suggest that none of the three largest floods in this intervening period (1901, 1936 and 1947) led to widespread inundation at Boroughbridge.

A5 Interpretation

Intervals between floods
The lack of a major flood in the period 1898 to 1968 undoubtedly reduced the level of general awareness of the significant risk of flooding at Boroughbridge. Topham (c. 1930) remarks: "The fact that Boroughbridge experienced a flood in 1883 is pretty generally known, but any idea of the severity of the same, and the distress it caused locally, is on the whole very vague." Extrapolation from this comment suggests that public perception of flood risk, and flood effects, in Boroughbridge would have been minimal by the 1950s and 1960s.

The intervals between major floods since 1968 are reminiscent of those seen in the late 19th-century. Thus the 4-year interval between 1991 and 1995 had precedents in the 6, 2 and 6-year intervals between floods in 1862 and 1868, 1881 and 1883, and 1892 and 1898. There is also a precedent for three major floods within 14 years (i.e. 1982, 1991 and 1995) in the sequence of floods occurring in 1881, 1883 and 1892.

Event characteristics
It can be noted that some events yield major floods at both Boroughbridge and York (e.g. 1982 and 1991), some yield a major flood at Boroughbridge but not York (e.g. 1822, 1883 and 1995), and some yield a major flood at York but not Boroughbridge (e.g. 1831 and 1947). With regard to Boroughbridge, snowmelt is thought to be a partial factor in more than half of major floods, and a major factor in at least half of the very largest floods (notably, 1881, 1883 and 1982). Many of the highest-impact floods come from rainfall, or rain and snowmelt, events of relatively long duration. Snowmelt events, and long-duration rainfall events, are more likely to be spatially extensive than short-duration rainfall extremes. The relatively large drainage basin of the Ure predisposes it to flooding from events of 2 or 3-day duration, and this sensitivity is further accentuated by the delaying effect of floodplain storage along much of the river's course. An intense flood of short duration is likely to be attenuated by this natural storage action. Section 9.5 of the main text reports that the relative magnitude of concurrent flows in the Swale has negligible impact on flooding at Boroughbridge. However, it would nevertheless be informative to know more about flood levels in the Swale during the January 1883 flood, which was an extreme flood of particularly long duration.

Swale
The historical review has not focused on flooding on the Swale. Three events identified that may have given rise to extreme floods on the Swale are March 1881, January 1883 and January 1890. The age of these events is particularly worrying. How can the perception of flood risk from the Swale be sustained if there has been no outstanding flood in 100 years? The dearth of historical data for the Swale may reflect that the river affects fewer major settlements (Richmond and Catterick Bridge?). However, it may also reflect the greater attenuating effect of floodplain storage along the Swale. The natural response characteristics of the Swale are such that it is likely to be sensitive to rainfall and rain/snowmelt events of somewhat longer duration (e.g. three to four days, rather than two to three days for the Ure). The historical review undertaken in this study should be strengthened if it is to be used in the assessment of flood risk for sites on the Swale.

Climate change
The general impact of climate change on flood frequency in UK rivers is uncertain. This is because the impact of climate change on rainfall is much less well understood than that on temperature. The review has shown that snowmelt is an important ingredient of at least half of major floods at Boroughbridge. A warmer climate will mean less frequent large accumulations of snow, giving fewer opportunities for snowmelt events of long duration. Thus the impact of global climate change on flooding at Boroughbridge may not necessarily be to increase flood frequency. There is no evidence of systematic trend in flood frequency at Boroughbridge, and it is reasonable to conclude that the flood behaviour of the Ure is merely highly variable.

Land-use change
It would be interesting to see a copy of Clarke's c. 1863 paper to the Boroughbridge Agricultural Society on *Land draining*, and also the later ones by Leadman (1881 and c. 1885) which give an agricultural perspective on floods and flood prevention. Creer (1892) remarks: "The improved system of draining now adopted for agricultural land, and the greater extent of land under drainage as compared with 60 years ago, leads me to believe that floods are likely to be more frequent and severe than formerly, although they are not likely to be of such long duration." This illustrates that fears that agricultural practices aggravate flood risk are not new. Reports of the January 1883 event speak of the flood rising very rapidly, as was said (for example) of the January 1982 flood. There does not seem to be any clear evidence that field drainage has had any stronger effect in recent years than formerly.

Leadman's 1881 paper (copy not seen) might reveal whether the 19th century saw notable increases in the areas of riparian land protected from frequent flooding. However, from such old maps that have been seen, it would appear that there is a long history of embanking to protect agricultural land alongside the Ure. The effect of a particular flood protection scheme is to increase the frequency of flooding of unprotected sites downstream. However, the effects are likely to be fairly modest. For sites that are vulnerable to flooding only in extreme events, the effect of embanking natural flood meadows may be beneficial to downstream sites, provided that these upstream embankments overtop before inundation occurs at the site of concern.

Sheep

Sansom (1996) expresses the view that overstocking of sheep in the Yorkshire Dales may degrade vegetation leading to increased soil erosion and increased runoff. Such an effect is difficult to prove or disprove. The natural variability of flood occurrences is too great to allow the detection of underlying trends in flood frequency with confidence, unless the effects are very dramatic (e.g. arising from extensive urbanisation). They are especially difficult to discern on large catchments.

The interpretation made by Sansom is partly based on historical flood data for Mickley weir. Environment Agency staff were unable to confirm the position at which the more recent floods have been measured, and whether these levels have been adjusted to be consistent with the 1862 and 1868 flood marks taken from a river-side building some distance downstream of the weir. These are possibly minor effects. However, the omission, from the series of flood data at Mickley (Sansom, 1996), of four major floods in the late 19th-century (1881, 1883, 1892 and 1898) misrepresents the flood history of the Ure, and further weakens the argument.

Flood protection in Boroughbridge town

The historical review has revealed inherent flooding problems at Boroughbridge, arising from its siting at the Tutt confluence with the Ure. Parts of the town are particularly low-lying, and — prior to the Tutt diversion scheme built in 1987 — flood-water from the Ure typically entered the town by reverse flow up the lower reaches of the Tutt. This liability is well illustrated by the embankments shown alongside the Tutt in 1901 (see Figure A.2).

Boroughbridge town is now protected by what amounts to a bunded flood defence, with embankments on all sides. The Tutt diversion scheme would appear to be an imaginative solution to a difficult flooding problem. Had the Aldborough cross-bank been constructed to a more appropriate level in 1987, it is possible that the scheme would have been judged a considerable success: reducing or averting inundation in the major floods of 1991 and 1995.

It is evident from information seen in local libraries, and other sources, that flood risk is a source of concern to many Boroughbridge residents and businesses. Some of this concern is well placed, because of the vulnerable siting of Boroughbridge town. Well-maintained flood defences have much to offer Boroughbridge in reducing the frequency of inundation. However, some degree of flood risk will always remain, and residents should be reminded of the long history of Ure floods and the fact even the severe flood of January 1883 will one day be exceeded, perhaps handsomely.

Islands

The entries for 1766-71 and 1909 in Section A.3 indicate that there have been islands in the Ure close to Boroughbridge, both before construction of Westwick and Boroughbridge weirs (see entry for 1766-71) and subsequently (see entry for 1901).

Return periods

Because of the irregular pattern of occurrence of major floods at Boroughbridge in the last 200 years - with many floods in the late 19th and late 20th centuries, but no major event between 1898 and 1968 - the return periods of extreme floods such as the January 1883 and February 1991 events are difficult to estimate with great certainty. However, it is possible to be somewhat more confident about the return period of lesser events such as the March 1968 flood. It is estimated that the flood level experienced in the 1968 event has been exceeded about ten times in 200 years. This means that the average interval between years containing a flood greater than this is about 20 years. [According to the Gringorten plotting position formula, the 10th largest value in a set of 200 values plots at a return period of 20.9 years.] Thus the historical review suggests that the gauged peak discharge of 400 m^3s^{-1} on 24 March 1968 provides an estimate of the 20-year peak flow at Westwick. This inference is moderated in Section 8.4 of the main report, when estimates by a particular flood frequency distribution are preferred.

A6 Augmentation of review

It is suggested above that the historical review has captured the dates of the largest eight to 12 floods in the last 200 years. If a major event has been missed, it seems most likely that this would have been in the first 20 years of this period, i.e. prior to the 1822 flood. However, cutting the historical review immediately before the 1822 event was resisted because it would have introduced bias.

The main task in augmenting the review would be to seek to confirm the flood chronology by searching additional sources, particularly local newspapers. Revisiting the searches of Ripon newspapers (undertaken as part of this study) and of York and Leeds newspapers (reported by Radley and Simms, 1970) — guided by the dates given above — would undoubtedly reveal new details that might allow the tentative ranking of the largest floods to be strengthened. Newspapers covering the early part of the period include the York Courant (from 1725) and the Leeds Intelligencer (from 1754) and Leeds Mercury (from 1767). Some of the Ripon newspapers inspected during the study were in relatively poor condition.

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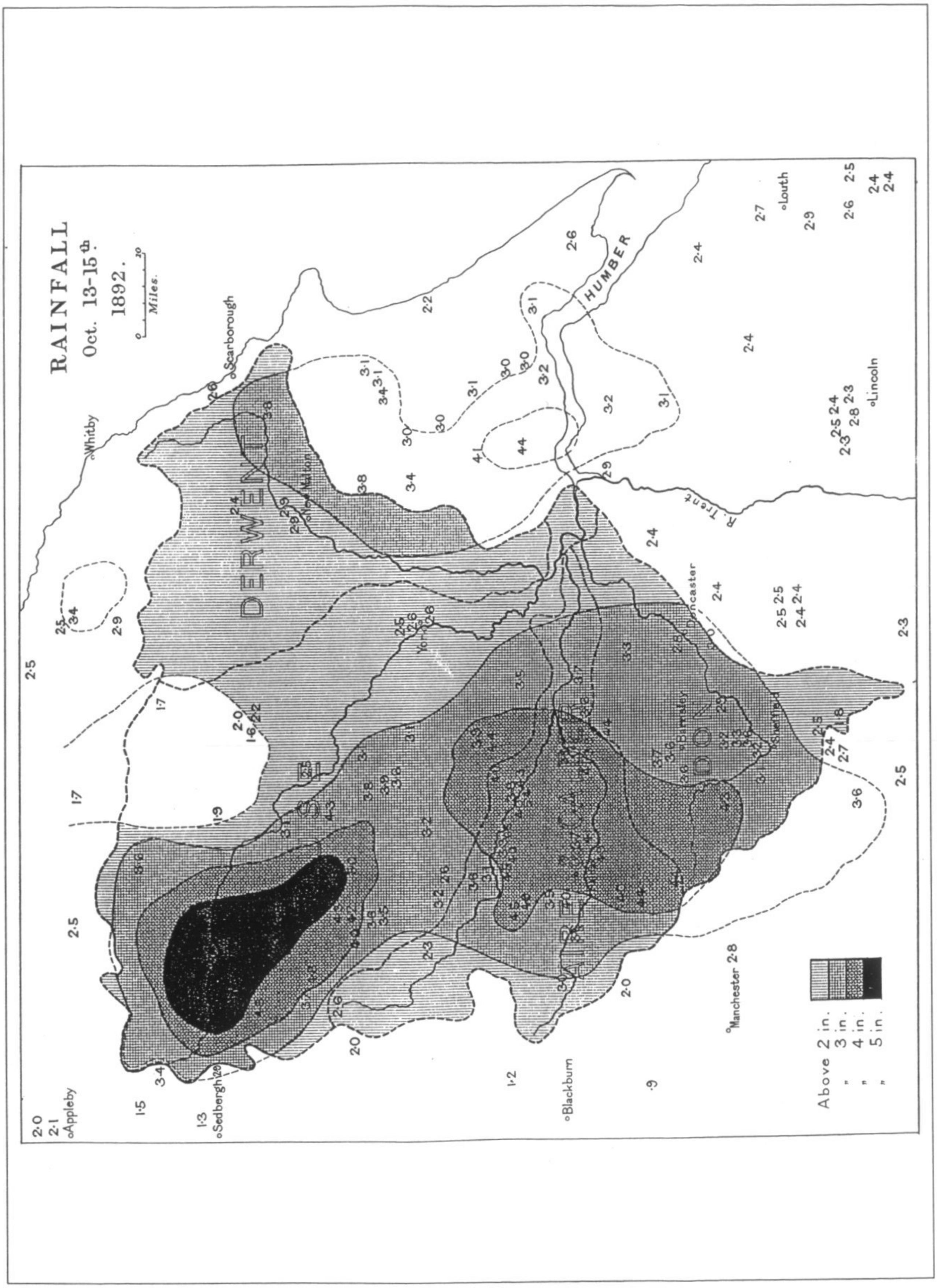

Figure A1 Depths and isohyets for 3-day rainfall, 13-15 October 1892 (source: British Rainfall, 1892)

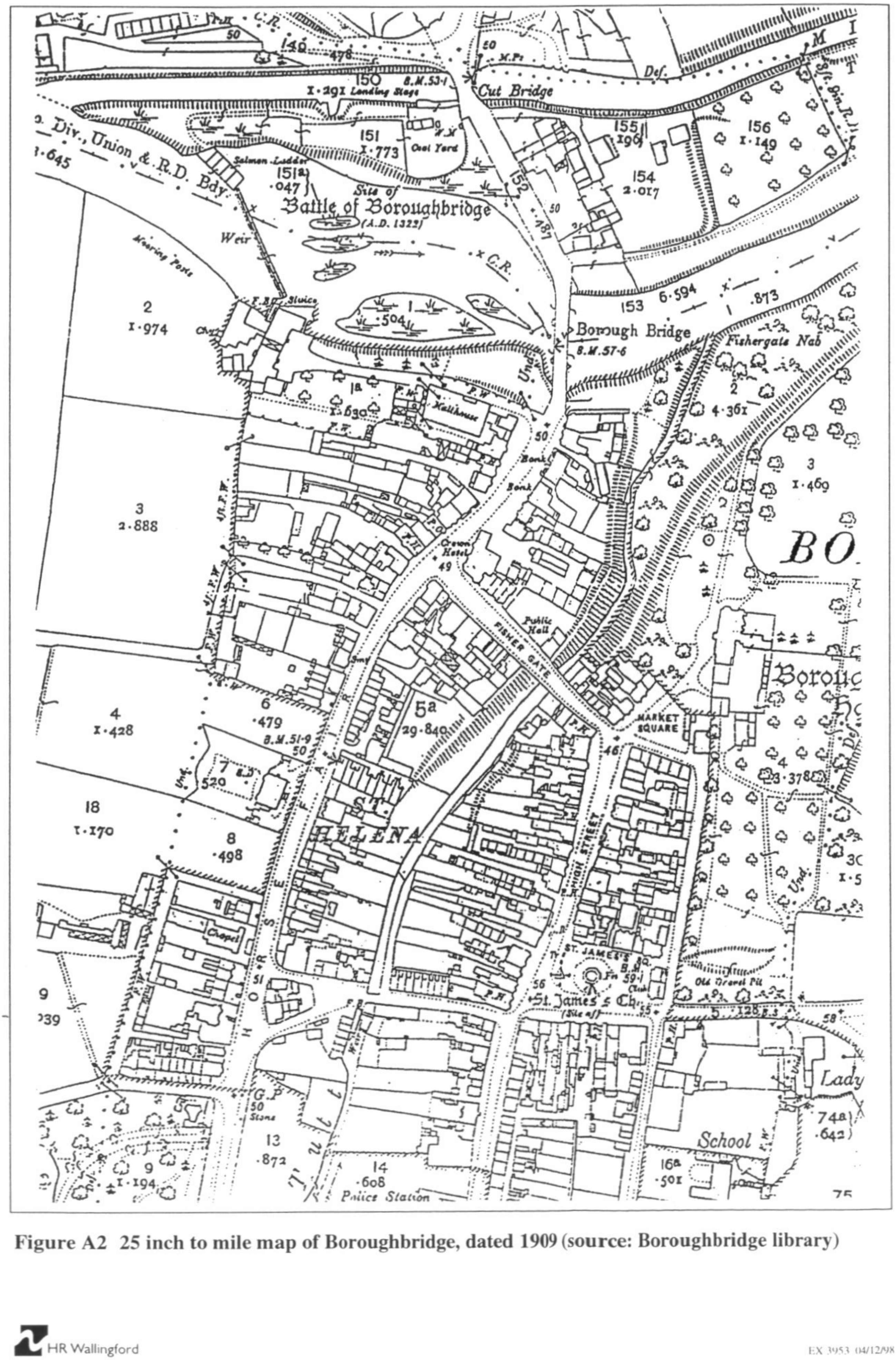

Figure A2 25 inch to mile map of Boroughbridge, dated 1909 (source: Boroughbridge library)

Figure A3 6 inch to mile map of Boroughbridge and district, dated 1910 (source: Boroughbridge library)