FLOODING THROUGH THE AGES

Reconstructing historical floods in the city of Bath

IOANNA STAMATAKI & THOMAS R. KJELDSEN

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Ioanna Stamataki & Thomas R. Kjeldsen

The HYDRIC BATH Project aimed to investigate and assess the utility of documentary evidence of past flood events (1823-1960) with contemporary flood risk assessments. The project focussed on the River Avon in Bath, because of the availability of clear historical evidence of past events, primarily physical flood marks on buildings and bridges, but also a well-documented history of flooding through sources such as photographs, technical reports and previous research.

This book accomplishes the project website https://hydricbath.weebly.com/ detailing the work undertaken as part of the HYDRIC BATH project, funded by the Leverhulme Trust (2017-2020).

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CONTENTS

FOREWORD

I am very pleased to foreword this monograph telling the story of how attempts to combat historical flood in the city of Bath have shaped the city and its river as we know it today. The material in the book originates from research undertaken at the Department of Architecture and Civil Engineering and generously funded by the Leverhulme Trust. The University of Bath is a signatory to the Manifesto for Public Engagement and strongly believes in our responsibility to contribute to society and local communities through public engagement, and that we as a university have much to gain in return from this engagement. It is my sincere wish that the material presented in this publication will be of interest to the reader and will generate further conversations about our relationship with the River Avon and our natural environment more broadly.

Professor Ian H White
Vice-Chancellor and President of the University of Bath
Bath, November 2020

PREFACE

This book contains a summary of the HYDRIC BATH research project reconstructing the hydrological and hydraulic aspects of historical floods in the city of Bath. The aim of the project was two-fold. Firstly, to investigate how these past events, and the efforts of the city's inhabitants to combat flood risk, have shaped the city and its relationship with the river. Secondly, through a detailed reconstruction of the river and the changes to its hydraulic properties over the past two centuries, to use advanced hydraulic modelling to assess the magnitude of these past events. It is hoped that the results from the project will be of interest to ongoing efforts in understanding current and future flood events in the context of past events, to people interested in the history of Bath and its relationship with the River Avon, and to everyone with a general interest in environmental history.

The city of Bath is a historical UNESCO world-heritage site and is an instructive case study in how the history, architecture and development of a city can be closely connected to the city's relationship with its river. The River Avon (also known as the Bristol Avon) rises in South Gloucestershire and flows through the Wiltshire town of Chippenham before reaching the centre of Bath and onwards to Bristol, ultimately flowing into the Bristol Channel at Avonmouth. The Environment Agency is operating a number of river flow gauging stations on the river; the most central to this study is the station situated at Bathford, just upstream from Bath itself, at which point the upstream catchment area is 1552 km^2. This study was particularly concerned about the stretch of river from Bathford (approximately 3 km upstream of Bath city centre) down to Twerton Sluices on the Western side of Bath from where the river flows down to Bristol City.

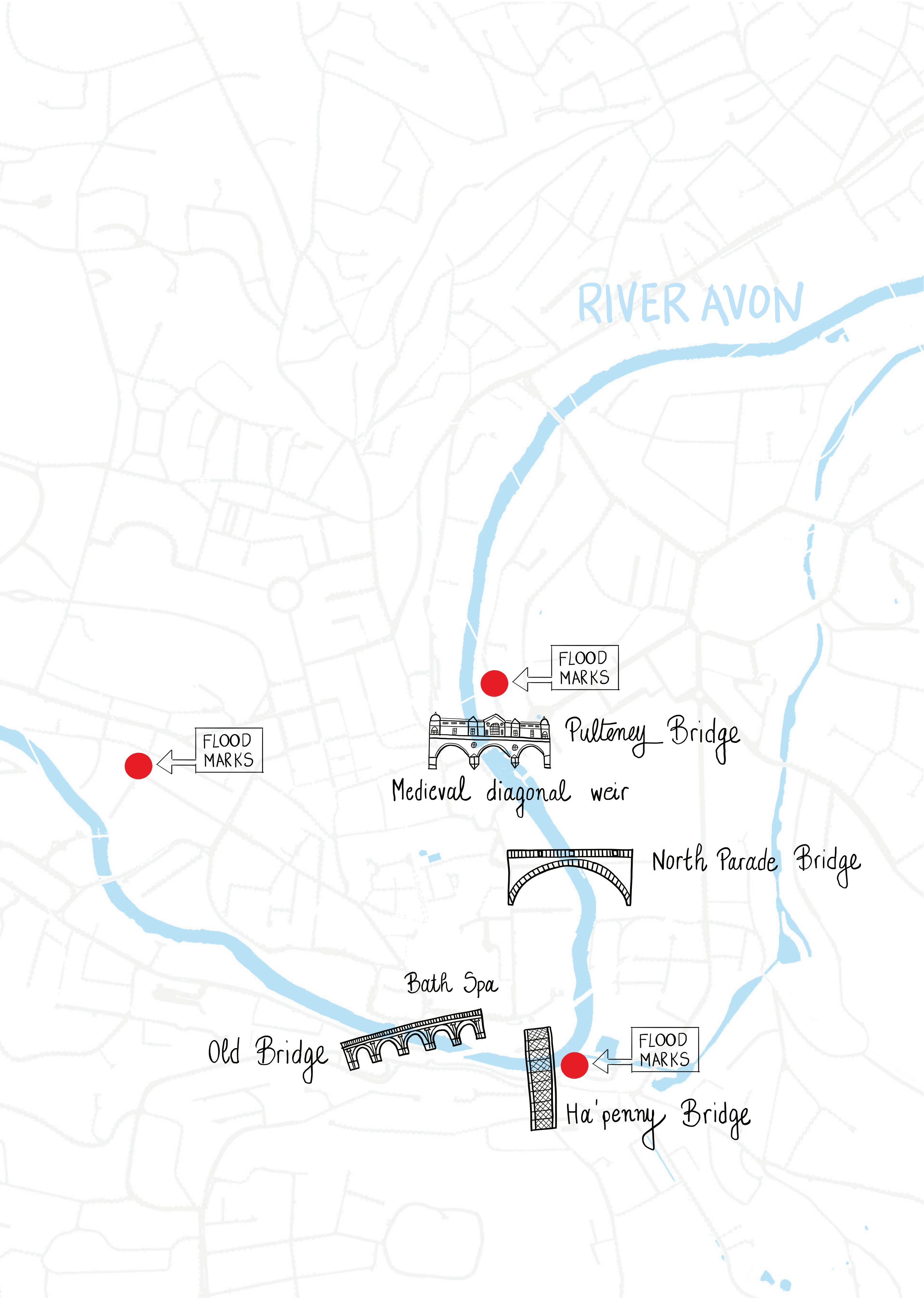
Following a severe flood event in December 1960, the city embarked on the design and construction of the Bath Flood Protection Scheme, which was completed in 1974, and appears to have kept the city safe from major flooding ever since. However, prior to the construction of the Bath Flood Protection Scheme, flooding of the city centre and the areas close to the River Avon were regular occurrences. Evidence of these historical events have been captured by a variety of sources, including photographs, newspaper reports, technical engineering reports, and actual physical flood level marks on bridges and buildings. By compiling all this information, the HYDRIC BATH Project has managed to reconstruct the hydrological and hydraulic conditions of these past flood events. Past efforts to protect against and mitigate the impact of flooding are in large parts responsible for the river and its environments as they exist today as demonstrated in this book. Finally, we hope that more in-depth knowledge of these past events will help to put current extreme flood events into a longer historical perspective than is currently possible based on limited records of observed river flow.

A major effort of the project was the construction of a hydraulic model representing the geometry of the River Avon and the associated hydraulic structures at the time of historical flood events. Members of the project team spend countless hours trawling through archive material stored in the Bath Record Office, and the archive room at the Environment Agency's offices in Bridgewater. The project team is indebted to the people offering kind assistance and sharing of their valuable knowledge at both locations; without this generosity, the successful completion of the project would not have been possible. The authors would also like to show their gratitude to Jacobs for providing a Flood Modeller license allowing them to undertake this research.

The project was kindly funded by the Leverhulme Trust, who's generosity is acknowledged with gratitude.

Dr Thomas R. Kjeldsen
Dr Ioanna Stamataki
Bath, November 2020

Map of BATH


RIVER AVON
FLOOD MARKS
Pulteney Bridge
FLOOD MARKS
Medieval diagonal weir
North Parade Bridge
Bath Spa
Old Bridge
FLOOD MARKS
Ha'penny Bridge

1
INTRODUCTION

The first known settlement in Bath (named Aquae Sulis), was founded around 44AD by the Romans, and by 50AD a temple and public baths had been constructed around the hot springs to exploit their healing properties. The Savile Map of Bath (Fig. 1.1), dated 1603, shows the extent of the Elizabethan city and provides the first sighting of a weir in the city centre, a medieval diagonal weir establishing a water level difference to power Monk's Mill (Davis et al., 2006). More weirs and locks were built in 1727 by Architect John Wood the Elder (1704-1754) to improve the Avon Navigation, control the tidal river and conduct boats uphill and upstream to Bath. Making the River Avon navigable brought economic prosperity to the area allowing Bath to become an inland port supporting agriculture and the burgeoning industrialisation economy (Buchanan, 1998). In the 18th century Georgian period the city was considered a spa city and there was an increase in population and development with neoclassical Palladian buildings.

Bath has always had a mixed relationship with the River Avon. From the late 19th century the River Avon no longer served an economic

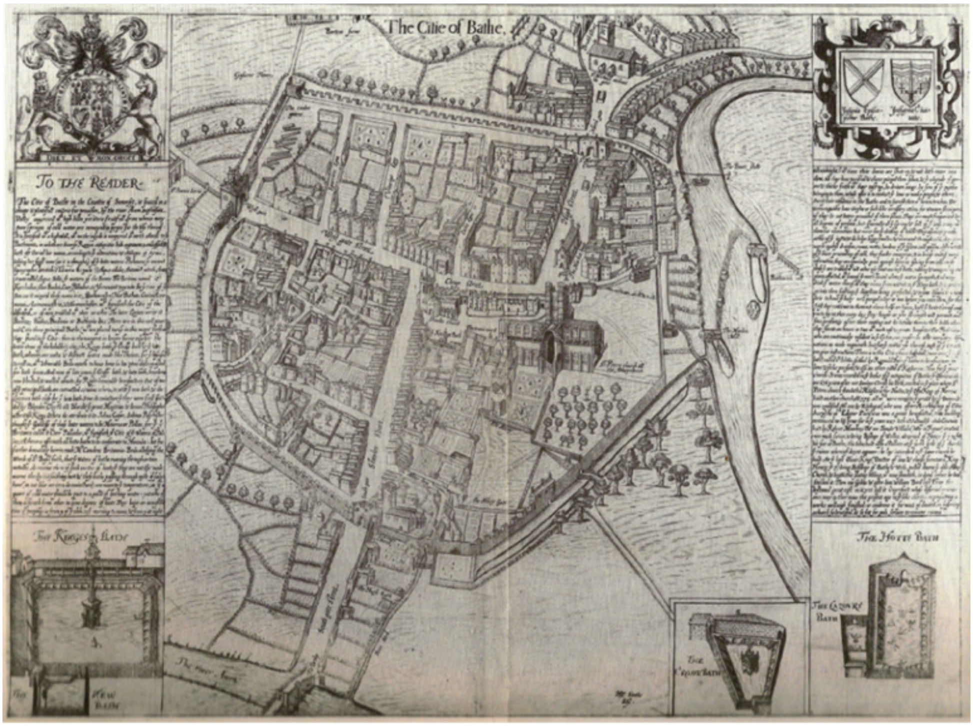


Fig. 1.1 The Savile Map of 1603, historical map of the city of Bath, showing the first sighting of a weir in Bath's city centre, a medieval diagonal weir highlighted in the map by the dashed rectangle (Manco, 1993)

purpose (River Corridor Group, 2011). Only in recent years have new developments such as Bath Quays Waterside started promoting river living as desirable and reconnecting Bath to its river, whereas most historical buildings located riverside are facing away from the river; resembling the city turning its back on flooding.

As the city was always located close to the river, communities in Bath have experienced the effects of flooding since the Roman times (Fig. 1.2). The history of efforts combating the scourge of flooding has been documented in illustrious accounts by, among others, Buchanan (1998) and Greenhalgh (1974), citing evidence of flooding, though physical evidence has so far only been identified for the 19th century onwards.

Historical evidence of past flood events is left on buildings in the city in the form of water level marks as well as documentary evidence in contemporary newspapers and technical reports (Fig. 1.3). There

Fig. 1.2 Photographs of the 1960 flood by Bath in Time. Photograph of swans on Southgate Street (left) and flooded Oak street (right) (Bath in Time, 2019)

are three locations (refer to map on page 8) where dated historical water levels have been identified within the city: Grove Street, Norfolk buildings and Halfpenny/Widcombe Bridge. The earliest flood mark dates back to 1823 in Grove Street but the majority of extreme floods after that have been recorded underneath Halfpenny Bridge (fourteen marks from 1875 to 1960). These historical flood marks predate existing flow recordings initiated in 1939 and 1969, respectively, and located further upstream at St James Bridge (1939-1968) and Bathford (1969-present), and therefore provide a unique opportunity to extend the record length in time and to include significant events. It is important though to remember that the historical flood marks represent the hydraulic conditions existing at the time of the flood. As detailed in this book, these conditions changed considerable during the 20th century, necessitating detailed hydraulic analysis to reconstruct these events. Using the software Flood Modeller (Jacobs, 2020) a 1D hydraulic model of the River Avon was constructed by combining the data representing the river geometry and the hydrology.

This book is organised into 10 chapters presenting and discussing evidence of past flood events and their impact on the River Avon in the city of Bath. The first chapter is an introduction, the following 6 chapters cover important aspects of the flood history, including: the history of flooding, past efforts to protect the city against flooding, and key locations of significant importance to the flooding in the city.

The last 2 chapters detail efforts undertaken as part of the research project to reconstruct the hydrological and hydraulic conditions of the historical flood events. The final chapter concludes on the importance of this work.

Fig. 1.3 Photograph of the 1960 flood. Flood on the Lower Bristol Road (Bath in Time, 2019)

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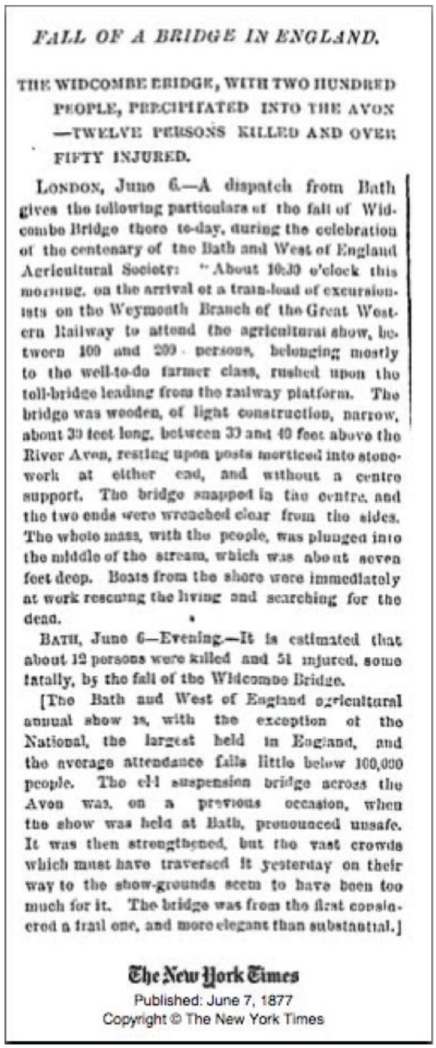
2

THE FLOOD MARKS OF HA'PENNY BRIDGE

Have you seen the floodmarks of Ha'penny Bridge?

Bath's Halfpenny Bridge spans over the River Avon connecting Widcombe to the city Centre. Historically, the first bridge in this location was built in 1863 by Hicks & Isaacs and it was a 100ft (=30.48 m) timber double bow string trussed bridge. Like many bridges with the same name, Halfpenny Bridge was a pedestrian toll bridge with a toll of half a penny per person, thus called Ha'penny Bridge. On June 6th 1877 disaster struck in Bath, when hundreds of tourists congregated on the bridge



FALL OF A BRIDGE IN ENGLAND.

THE WIDCOMBE BRIDGE, WITH TWO HUNDRED PEOPLE, PRECIPITATED INTO THE AVON —TWELVE PERSONS KILLED AND OVER FIFTY INJURED.

LONDON, June 6.—A dispatch from Bath gives the following particulars of the fall of Widcombe Bridge there to-day, during the celebration of the centenary of the Bath and West of England Agricultural Society: "About 10:30 o'clock this morning, on the arrival of a train-load of excursionists on the Weymouth Branch of the Great Western Railway to attend the agricultural show, between 100 and 200 persons, belonging mostly to the well-to-do farmer class, rushed upon the toll-bridge leading from the railway platform. The bridge was wooden, of light construction, narrow, about 30 feet long, between 30 and 40 feet above the River Avon, resting upon posts morticed into stonework at either end, and without a centre support. The bridge snapped in the centre, and the two ends were wrenched clear from the sides. The whole mass, with the people, was plunged into the middle of the stream, which was about seven feet deep. Boats from the shore were immediately at work rescuing the living and searching for the dead.

BATH, June 6—Evening.—It is estimated that about 12 persons were killed and 51 injured, some fatally, by the fall of the Widcombe Bridge.

[The Bath and West of England agricultural annual show is, with the exception of the National, the largest held in England, and the average attendance falls little below 100,000 people. The old suspension bridge across the Avon was, on a previous occasion, when the show was held at Bath, pronounced unsafe. It was then strengthened, but the vast crowds which must have traversed it yesterday on their way to the show-grounds seem to have been too much for it. The bridge was from the first considered a frail one, and more elegant than substantial.]

The New York Times

Published: June 7, 1877

Fig. 2.1 (Left) Fall of a bridge in England, newspaper article dated June 7, 1877 in the The New York Times (1877)
Fig. 2.2 Photo of Halfpenny Bridge (2019) looking upstream towards Thimble Mill Pumping Station.

waiting to pay the toll to go to the Bath and West Show, a yearly agricultural show first established in 1852. The bridge was overloaded and collapsed by snapping in its centre, resulting to eight casualties and many injuries (Scott, 1993). The collapse was also reported by the New York Times (Fig. 2.1) with an article entitled “Fall of a bridge in England”. Later that year, a new bridge was designed by T. E. M. Marsh replacing the old bridge by a single-span wrought-iron lattice girder structure using the same piers (Fig. 2.2).

Would one walk on the river footpath from Thimble Mill Pumping Station towards Churchill Bridge on the Widcombe side, you will walk below Halfpenny Bridge (see Fig. 2.4). On the bridge’s buttress there are 16 engraved flood levels on the rock (see Fig. 2.3). The visible dates represented on the wall include: 1866, 1867, 1875, 1880, 1882, 1888, 1894, 1897, 1900, 1903, 1925, 1947, 1960.

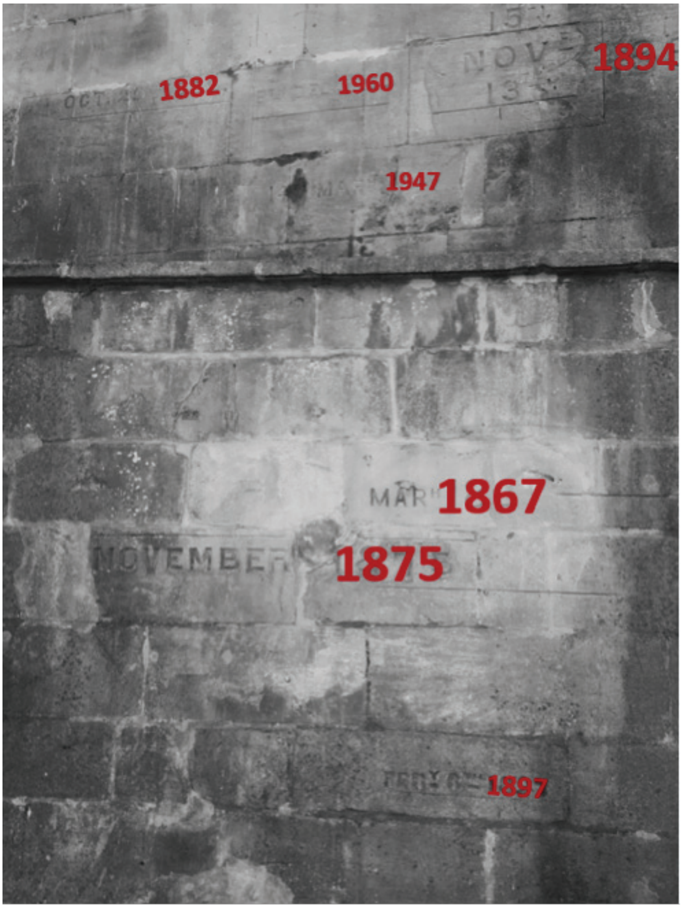


Fig. 2.3 Halfpenny Bridge Flood marks

Fig. 2.4 Google maps location of the Ha'penny Bridge flood marks (Google maps, 2020)

Most of these flood levels are extreme compared to current-day water levels. However, it is important to note that these levels represent the flood conditions in the river prior to the completion of the Bath Flood Protection Scheme and therefore reflect, in particular, the effect of Old Bridge (later replaced by Churchill Bridge) which was a 5-arch bridge that restricted and blocked the flow in many of these events. After the Bath Flood Protection Scheme (1964-1974) was put in place the floods were largely eliminated in the centre of Bath but to what extend this has to do with the scheme or whether equally extreme events (similar to the historical) have yet to occur remains a question.

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3
THE EVOLUTION OF FLOOD MANAGEMENT IN BATH

By Dr Chrysoula Papacharalampou

A visit to the Bath Record Office Archives and Local Stories (or Bath Record Office for short) of the Bath & East Somerset (B&NES) Council will reveal a hidden treasure of documentary evidence relating to the evolution of local flood policy (Fig. 3.1). This includes notes from the Council's (Major's) meetings, articles in the local press, correspondence between local stakeholders, industrial actors and citizens, extensive inventories/catalogues of on-site inspections and compensations bills.

The available evidence suggests that major historical flood events have been catalysts for policy change at the city level. A range of local policies, mainly focussing on a post-event response, were initiated and implemented by local stakeholders or 'policy entrepreneurs' (i.e. advocates for proposals) following the major flood events. This local and post-event policy development and implementation was due to the absence of government authorities for flood management in the United Kingdom until 1930, when the Land Drainage Act was enforced.

The policy entrepreneurs for the City of Bath included the Mayors of Bath, members of the local Council, engineers and local industry. The severity of each individual event in terms of its impact on the local communities appears to have shaped the action planning and decision-making. Public opinion and concern regarding flood events and their impact seem to have influenced the implementation of plans requiring local investment. The policy actions relate to three main areas: (1) citizen's relief, (2) infrastructure development, and (3) institutional change.

A number of initiatives to alleviate the distressed local population were launched mostly as an immediate response to major flood events.

Fig. 3.1 Photos from archive search in the Bath Record Office

FLOOD MANAGEMENT IN THE 19TH CENTURY

Relief funds and actions of social and corporate responsibility are extensively documented after the flood events of 1882 and 1894. The Mayor's Relief Fund following the 1882 flood, served to the provision of food supply, compensation for losses of assets and partial restoration of households. Evidence of the distribution of these relief funds can be retrieved in the Bath Record Office, inclusive of letters to the Flood Relief Committee (established as a response to the 1823 flood) requesting refunds for cattle which drowned during the event. Local industry showed their corporate responsibility by offering accommodation and tons of coal, whilst the police force made a public appeal for food and clothing supplies. The floods of 1894 (13th and 15th November, two distinct floods three-days apart) reported as 'most serious and calamitous' on record, had socio-economic impacts on the population: properties, business and trade stock were inundated, washed away or destroyed. These events triggered social response and raised actions of high social responsibility from citizens, local tradesmen and the policy force. The local authorities formulated an emergency committee aimed at relieving the distress. Similarly to past policies, actions of immediate relief included distribution of food (i.e. bread, cheese, coffee) distributed in baskets (kind offer of local bakeries and tradespeople/shops), offer of meals in public spaces, provision for accommodation and coal tickets, as the city experienced a complete gas and lighting cut-off. Two separate relief funds were raised (i.e. St James Relief Fund, Public Relief Fund), both aimed at alleviating the ones affected. Next to the measures for alleviating stress, post-flood policies relate to the safety of the local society at large, in the more recent years: after the 1960 flood, a Major Disaster Plan (outlining managing options for severe events) was assembled and new jobs were created within the local police force.

The historical records indicate flood mitigation in the City of Bath has mainly been focussed on engineering/infrastructure solutions. Reports for infrastructure projects were commissioned at multiple points in history, mainly triggered from a severe flood event, but implemented only when economic incentives and availability of public funds allowed. These reports outlined a series of preventive measures, including the replacement of bridges and the widening of the riverbanks. Available records of the reports show converging expert opinions on the mitigation solutions. For example, the 1823 flood resulted in the commission of an engineering report to the city engineer Thomas Telford in 1824, which recommended the removal of obstruction across the river channel and the replacement of the

Old Bridge by a single arch bridge. The total estimated costs for the solutions proposed (£50,000) did not lead to its fruition. Similarly, after the flood event in November 1875, further engineering recommendations were made in a report published by Alferd Mitchell, who suggested the use of weirs across the length of River Avon. The recommendations were aimed to increase the discharge capacity of the water system, but no further actions were taken at the time. In 1892, a decade after the 'surprising' 1882 devastating flood event, a new report outlined a series of infrastructure measures for future flood defence. The estimated cost (£100,000) of the flood defence measures was deemed immoderate to proceed with the implementation of the plan. The catastrophic events of 1894 resulted in the commission of yet another engineering report commissioned (1896) to G. Remington. This report outlined a radical suggestion: diversion of part of the floodwater of the River Avon through a tunnel of 86 sq. ft. (approx. 8 m^2) cross-sectional area. The estimated cost of the plan reached £69,300 and public concern regarding the impact of floods had grown, supporting a proactive approach to the mitigation of flooding. Yet, no plans were taken forward for implementation.

FLOOD MANAGEMENT IN THE 20TH CENTURY

In the beginning of the 20th century, a series of flood incidents were reported in Bath (1903, 1925, 1932, 1935, and 1936). There is limited documentary evidence on the impact or alleviation policies following the events. Nonetheless, these incidents coincide with the enactment of the Land Drainage Act (1930). This was aimed to launch a new set of administrative structures to effectively manage the drainage of low-lying land at a national level. As a result of its implementation at a local level, the Bristol Catchment Board was established as the first government authority managing the River Avon Catchment. Shortly after it was founded, the Bristol Catchment Board adopted a proactive approach to flood management. In addition, the launch of the Inland Water Survey in 1935 marked the beginning of data-driven flood management, with several gauging stations being installed across the country. In Bath, the gauging station of St James (central Bath) started its operation in 1939, as proven by the available records of daily flow.

CONCLUSION

Considering the flood policy development in the City of Bath, a pattern emerges: throughout the 19th century, and despite the severity, impact and frequent of flood events, no coherent or preventive policy was implemented due to a lack of funds and sense of urgency among the citizens. The emergence of a government authority responsible for mitigating flood impacts, coupled with the convergence of public opinion and political priorities enabled the development and implementation of prominent and potent policy agenda.

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4
THE BATH FLOOD PROTECTION SCHEME

The relationship of Bath with the River Avon has always been mixed as although it relied upon the river to prosper, from early on the city also faced the catastrophic effects of flooding. This chapter will describe the different schemes and solutions proposed from 1823 and how these led to the current Bath Flood Protection Scheme.

Following flooding in 1823 (flood marks can be found in Grove Street) a Flood Relief Committee was formed, who commissioned Thomas Telford (a famous engineer of the time) to propose a solution. His scheme was costed at about £47,000 (£5,311,000 in today's money) and included removal of obstacles such as the five arch Old Bridge (present day Churchill Bridge) and re-alignment of channel section to increase flow capacity. However, at the time the scheme was considered too expensive and never materialised. Instead, people and businesses impacted by flooding were compensated by the Mayor's Relief fund.

Following a record-breaking flood event in October 1882 (Fig. 4.1), the Bath Cooperation commissioned another report into flood defence

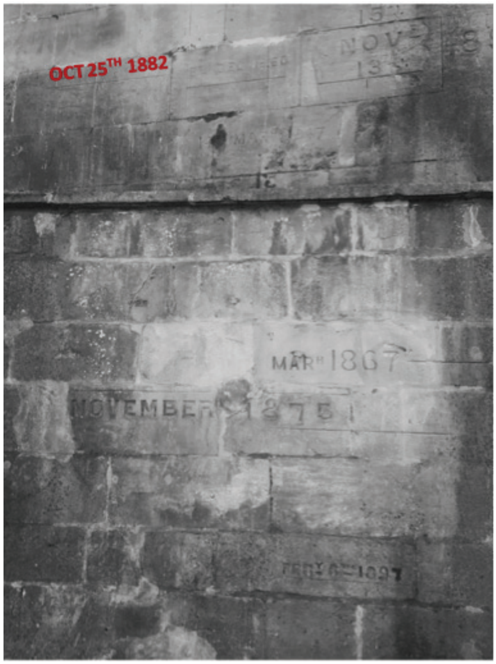


Fig. 4.1 October 1882 flood mark under Half-penny bridge

options, which resulted in a scheme designed by Messrs Coode, Son and Matthews proposing a series of infrastructure measures which included: deepening of the river, enhancement of existing weirs, replacement of Old Bridge and enhancement of existing bridges with steel sheet piles. His scheme was estimated at about £100,000 (£12,058,301 in today's money). Following this, a more imaginative scheme was proposed after the two distinct floods of 13th and 15th November 1894 by Mr Remmington, a London-based engineer, who in 1896 proposed a by-pass channel from Limpley Stoke Valley to below Twerton. Neither schemes were ever carried through to construction.

Extensive flooding followed in 1947 and again in 1953, and the-then chief engineer Frank Greenhalgh (Chief Engineer) initiated work on what would eventually become the present-day Bath Flood Protection Scheme. A scheme proposed some years earlier by Mr Greenhalgh's predecessor, Mr Mercer, similar to the 1882 scheme, had been abandoned at the outbreak of WW2.

Four options were initially considered for the flood defence scheme:

1. Construction of a by-pass channel either through Bath or via tunnelling under Combe Down.
2. Construction of a large storage reservoir or flood control dam upstream of Bath.
3. Construction of new embankments and walls along the riverbanks within the city.
4. Increase capacity of the river to carry flood water by removing obstacles such as bridges, dredging and streamlining the river channel.

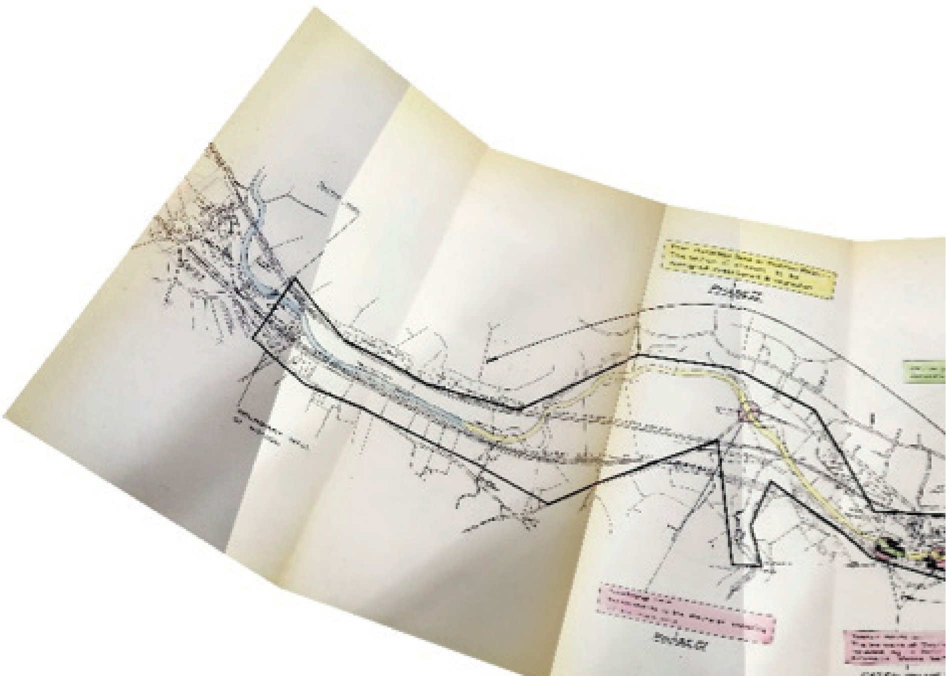
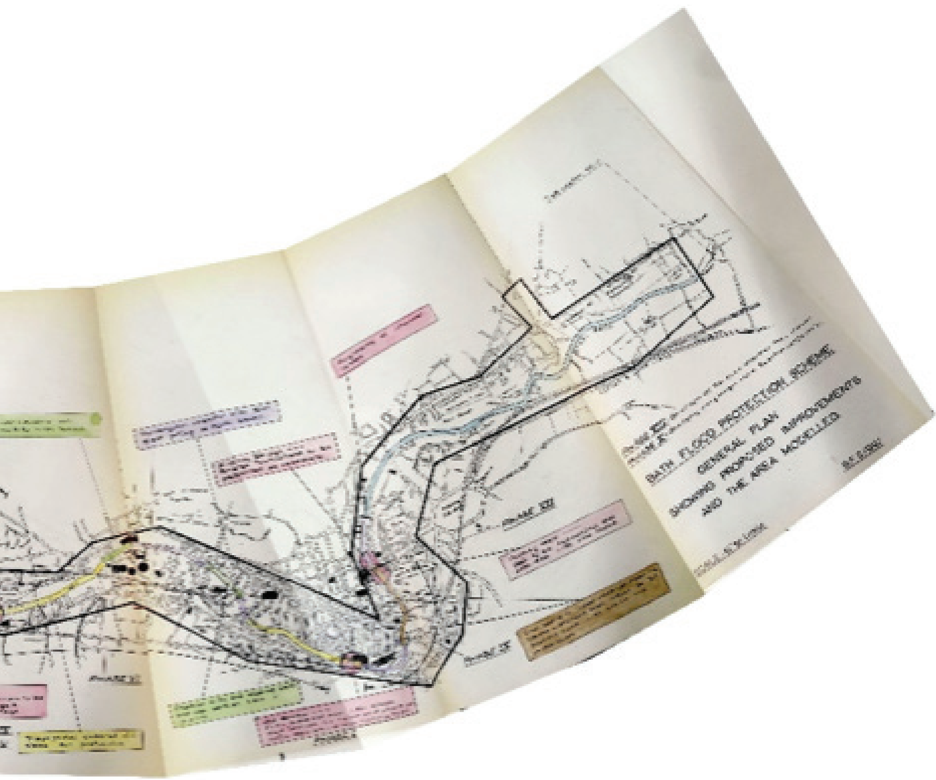


Fig. 4.2 Map of the River Avon showing the the phases of the Bath Flood Protection Scheme (photographed from the Environment Agency's archives)

The first option was considered uneconomical, and no suitable location with sufficient space could be identified near Bath for the second option. The third option was presumably unsightly as well as there were concerns about seepage and lack of drainage facilities. As a result, the fourth option was chosen, noticing its resemblance to the original scheme proposed in 1823 by Thomas Telford. The implementation of the Bath Flood Protection Scheme consisted of ten phases summarised below (Fig. 4.2).

<u>Phase I</u>: Replacement of Old Bridge with two single span bridges for road and pedestrian traffic (Fig. 4.3).

<u>Phase II</u>: Realignment, resection and regradement of river section between Horseshoe Bend and Twerton Gates.



Phase III: Improvement to the discharge capacity of the main arch in Newbridge.

Phase IV & V: Replacement of the two weirs at Twerton and replacement by a twin automatic sluice barrage.

Phase VI: Channel realignment and resection; trapezoidal channel sections with stone toe protection, channel sections with one sloped bank and one concrete vertical bank, and rectangular channel sections with steel sheet piling to both banks.

Phase VII: Pulteney Weir to be remodelled and provided with a new sluice gate, Pulteney Bridge foundations to be protected and regrading of channel ceases.

Phase VIII: Diversion of services wherever they occur.

Fig. 4.3 The Old Bridge from a plate by W. Watts, 1819 (Smith, 1948)

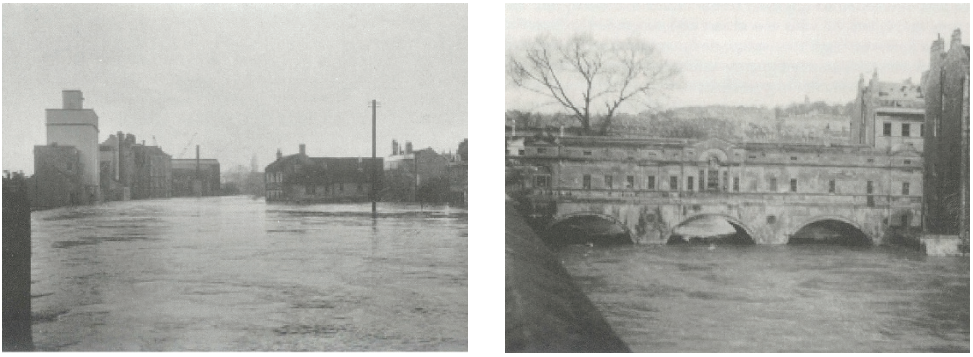


Fig. 4.4 Photographs of the 1960 flood by Rec. W.H. Parsons. Photograph looking downstream from Old Bridge (left) and Pulteney Bridge (right) (Buchanan, 1998)

Fig. 4.5 Photographs of the 1960 flood by Bath in Time (Bath in Time, 2019)

Phase IX: One bank to have a vertical masonry faced concrete wall and the other bank to be sloping earth with stone toe protection.

Phase X: Dredging along length from Twerton to U/S limit.

The scheme was designed to defend the city against the worst flood on record which at the time was considered to be the 1882 flood, estimated to have a peak flow of 12,950 cusecs (366.7 m^3/s). However, in December 1960 Bath experienced an even larger flood, peaking at an estimated flow rate of 424.4 m^3/s (this is estimated as the flood exceeded the capacity of the monitoring system).

The Bath Flood Protection Scheme has reduced the flood risk in Bath, but based on an information note produced by the Environment Agency and Bath & North East Somerset Council (2017) there are estimated to be over 500 properties (January 2017) in Bath at risk of flooding with a 1% chance of flooding in any one year, a number expected to increase in the future with climate change impact. The EA and B&NES work in partnership and continue to manage flood risk and provide future improvement solutions to the scheme.

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5
PULTENEY WEIR

The River Avon (also known as the Bristol Avon) flows from its source in Gloucestershire via Bath and into the sea at Avonmouth near Bristol. The name Avon was derived from a Celtic word meaning "river" and thus shares its name with some other rivers of the United Kingdom, Canada, New Zealand and Australia. In the city centre of Bath, Pulteney Bridge and Pulteney Weir sit majestically on the Avon, providing a beautiful view for residents and visitors alike (Fig. 5.1).

Pulteney Bridge was designed in 1769 by Robert Adam (Fig. 5.2). The bridge opened in 1770 and is an iconic structure in the city of Bath and is one of only four bridges in the world that has shops on both sides of its full span. Pulteney Weir is situated just downstream of Pulteney Bridge and is Bath's most recognisable hydraulic structure. The current weir was completed in 1975 and is part of the Bath Flood Protection Scheme implemented following the December 1960 flood to reduce the risk of flooding of the city. It is one of the many engineering obstructions built in the river's path to control flow; in 1972, it won a Civic Trust Award for "making an outstanding contribution to the appearance of the local scene". The modern-day Pulteney Weir is a complex shape that can be characterised as a 3-stepped, curved weir. Its three steps create a height difference of 1.5m between each of them with a lowered section in the centre of the weir serving as a fish pass. However, this was not the first weir to be constructed at this site.

Fig. 5.1 River Avon, Pulteney Bridge and Pulteney Weir

The Savile Map of Bath, dated 1603, shows the extent of the Elizabethan city and provides the first sighting of a weir in Bath's city centre, a medieval diagonal weir (Fig. 5.3). The purpose of the weir at the time was to establish a water level difference to power Monk's Mill. There were two mills on the Avon in Bath then, Monk's Mill located on the west bank of the river (current location of Parade Gardens with steps leading down to the river) and Bathwick Mill on the east bank (east of Pulteney Weir, where Pulteney Cruisers depart). The weir connected the two mills and a ferry was also in operation (marked on the 1603 map).

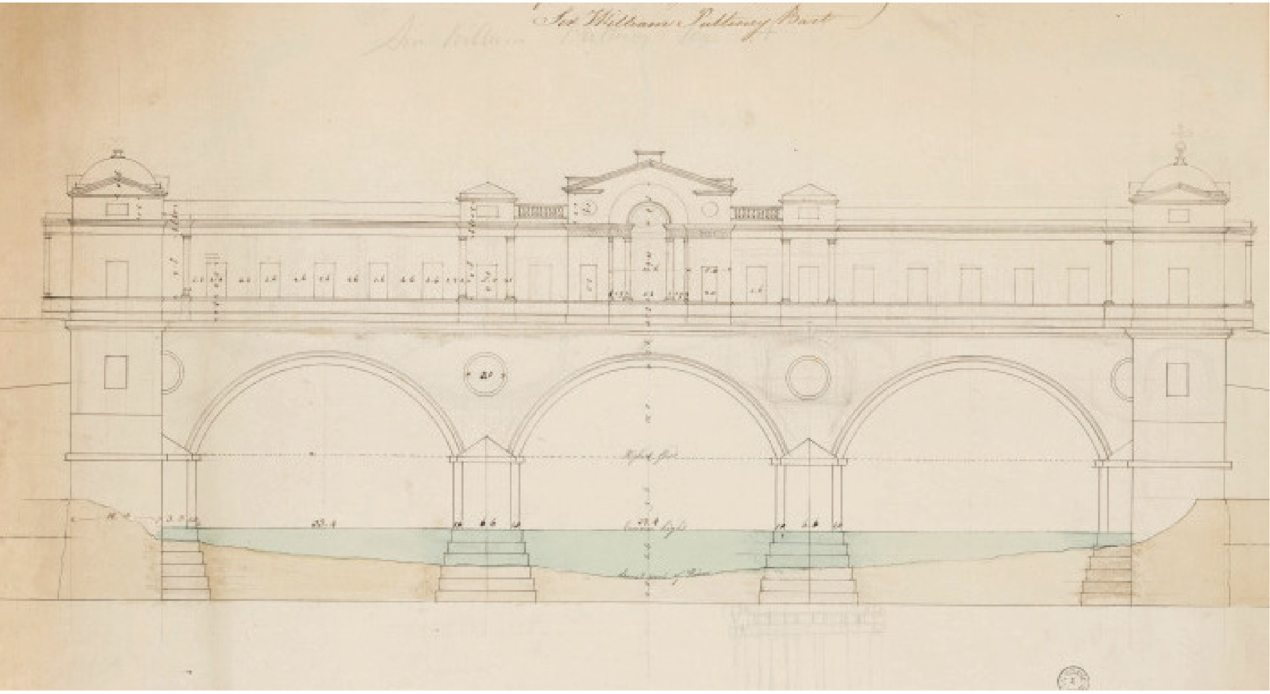

Fig. 5.2 Robert Adam's Pulteney Bridge Drawing (Adam, 1770)

The three historical maps in Fig. 5.3 show: (i) a map from a book entitled "A Guide to the knowledge of Bath, ancient and modern" by John Earle, found in the British Library archive dated 1572, (ii) the Savile Map of 1603, and (iii) a map from 1818 found in the book "The Historical and Local New Bath Guide: Embellished with eight original engravings, and a correct plan of the city" in the British Library archives. The map dated 1818 shows the old diagonal weir more clearly than the 1603 map; finally, the aerial photo of the city of Bath from 1946 (Fig. 5.4) also shows the old weir located in front of Pulteney Bridge.

Fig. 5.3 Historical maps of the city of Bath in 1572, 1603 and 1818

Today, Pulteney Weir is not simply a weir. It has become one of Bath's wonders as a beautifully made structure, both fulfilling its function and pleasing in its appearance.

Fun fact: Hollywood came to Bath in 2012 and Pulteney Weir was featured in the musical drama Les Misérables.

Fig. 5.4 Aerial photograph of the city of Bath in 1946 (Britain from Above, 1946)

SOURCES

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6

OLD BRIDGE

Fig. 6.1 Location of Churchill Bridge in Bath, UK (Google Maps, 2020)

Bridges are civil engineering structures that often have important historical significance. The city of Bath was built around the banks of the River Avon and the natural springs found in the area and thus the economic prosperity brought by these water features depended upon the construction of important transport routes to facilitate movement to and from the city. Permanent crossing points and bridges therefore played an crucial role from Roman times. In the last two centuries bridges became an important part of the city, not only for their practicality but also their elegance (Buchanan, 1990).

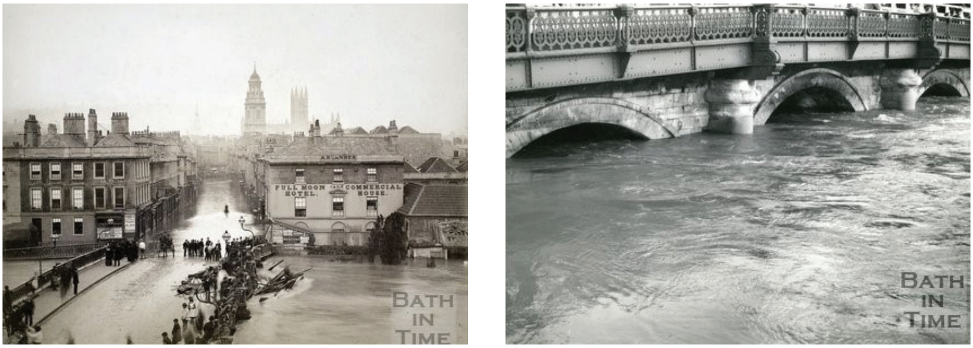


Fig. 6.2 Photographs of flooded Old Bridge in 1882 and 1960 (Bath in Time, 2019)

The present-day Churchill Bridge crossing the River Avon in the city centre (Fig. 6.3, right) is a single span bridge and represents one of the main routes connecting the centre of Bath to its southern suburbs (see Fig. 6.1). But there was not always a single span bridge at the location. In the past, where the current Churchill Bridge now stands, a five-arch stone bridge was constructed in 1754 called Old Bridge (Fig. 6.3, left) only to be replaced in 1965 by the current Churchill Bridge as part of the Bath Flood Protection Scheme. As discussed in previous chapters, the city of Bath has a long history of flooding going back centuries (Fig. 6.2), and after the important flood of 1960, the Bath Flood Protection Scheme (1964-1974) was initiated and consisted of ten phases aiming to incorporate different improvements to the river hydraulics. Specifically, Phase I of the scheme involved the replacement of Old Bridge with two single span bridges for road (Churchill Bridge) and pedestrian traffic.

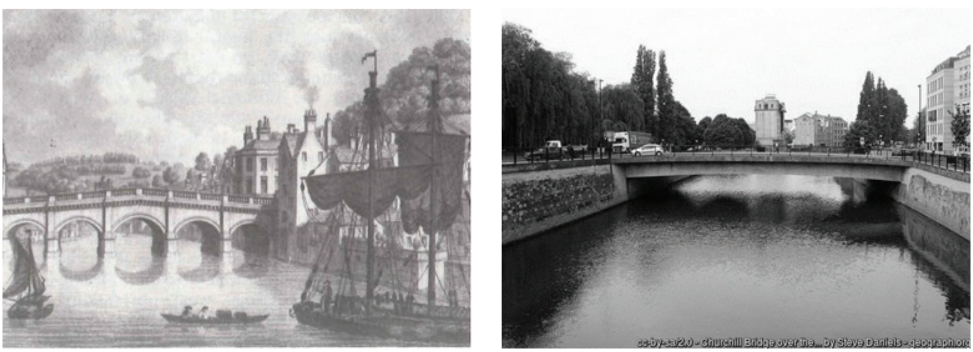
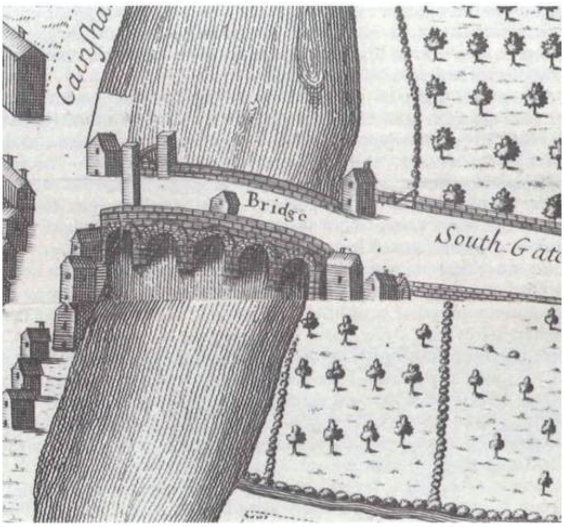


Fig. 6.3 River Avon, Old Bridge (left) and Churchill Bridge (right)

However, the story of Churchill Bridge starts much earlier during Roman times with a bridge aptly referred to as the Roman Bridge located at the same site; an area considered outside the city borders until 1590. There is evidence that a bridge was located there in 1273 (Buchanan, 1990) and it is believed that it was built before 1220 (Somerset HER, 1984), and that there probably was a wooden bridge at this site even earlier (Buchanan, 1990). At the time it was called St. Lawrence's Bridge (Somerset HER, 1984) and there were houses and a chapel dedicated to St Lawrence (Fig. 6.4), which survived until 1749, built on the bridge itself (Buchanan, 1990; Davis, 1857). Richard Jones designed Old Bridge which the Bath corporation built on the existing piers of St Lawrence's Bridge (Ison, 1980).

Wood (1765), describes Saint Laurence's Bridge in his book:



"it consisted of five apertures, covered with semi-circular arches: the top of the bridge is eleven feet six inches broad over the arches; but much wider over the abutments; and the buildings fronting it are the small chapel of Saint Lawrence, elevated over one of the piers, and four dwelling houses erected on the banks of the river, by the side of the abutments of the bridge".

Fig. 6.4 St Lawrence's Bridge as shown by Joseph Gilmore in 1694 in Bird (1986, p. 133)

The five-arch masonry bridge, Old Bridge, was identified very early as being prone to debris blocking and an obstacle to the river flow (Greenhalgh, 1974; Buchanan 1990). An engineering drawing of the bridge dated 1934 is shown in Figure 6.5. During the floods it was acting as a bottleneck and was retaining upstream the flood water and occasionally (e.g. 1823 flood) its arches were blocked by lots of timber (Buchanan 1990). Despite different attempts to refurbish the bridge, it remained the most important obstruction to the unrestricted flow of the River Avon on its way through Bath's city centre and consequently it was removed in 1964-1965 and replaced by the current single-span Churchill Bridge, thereby dramatically changing the hydraulic conditions of the river. The view of a flooded Saint Laurence's Bridge, and later Old Bridge (Fig. 6.2), with water covering the bridge parapets was a familiar image for the 18th and 19th century Bath residents (Buchanan, 1990).

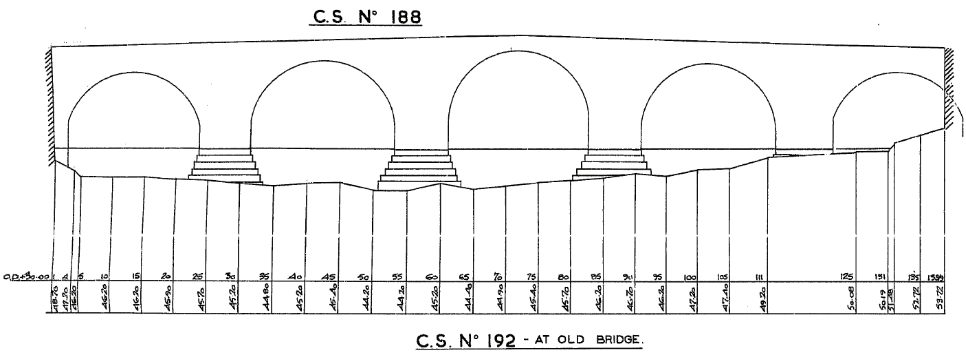


Fig. 6.5 Cross section at Old Bridge taken in 1934 (scanned drawing from the Environment Agency's Archives, Bridgwater)

Using the details extracted from the old engineering drawings, a modern hydraulic model was created using the Flood Modeller technical software tool and the effect on flood levels of the two different bridges (Old Bridge and Churchill Bridge) was investigated by considering their hydraulic performance during the 1960 flood (Fig. 6.6). This particular flood was considered a catalyst event for the policy of Bath as due to the city's development; the economic impacts were considerable.

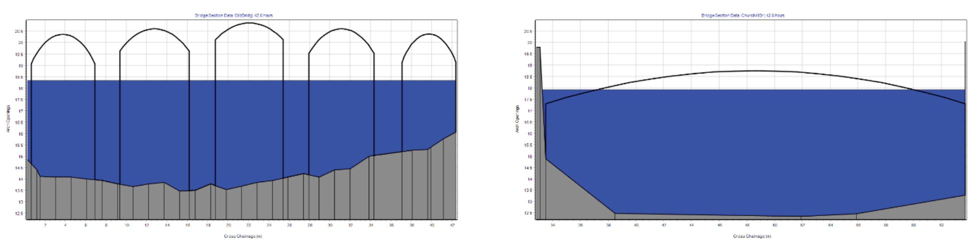


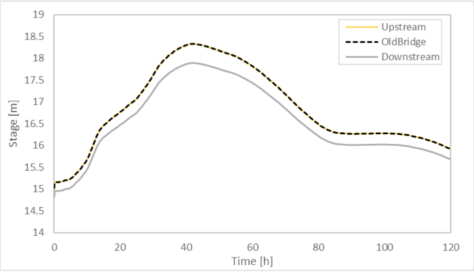
Fig. 6.6 Screenshot of numerical simulation during the 1960 flood event at Old Bridge (left) and Churchill Bridge (right)

To investigate the effect of the two bridges, the changes in water level (stage) were considered in three locations and the results are shown in Fig. 6.7:

1. Upstream of the bridge (yellow continuous line)
2. At the bridge location (black dashed line)
3. Downstream of the bridge (grey continuous line)

A way to understand the effect a bridge has in a water stream is to calculate its afflux which is the rise in water level (above normal) on the upstream side of a bridge (the side against the direction of the flow) caused by the effective reduction of the channel's width. The Flood Modeller software calculates the afflux on bridges using a method developed by HR Wallingford based experimental data (Brown, 1988). The two graphs on Fig. 6.7 show the stage (water depth) time series for Old Bridge (left) and Churchill Bridge (right) during the 1960 flood. It is noticeable that Old Bridge created a 0.5 metre surge in water level upstream and at the bridge location when compared to the Churchill Bridge because of its geometry restricting flow.

Even though the hydraulic behaviour of river systems is complex, especially when hydraulic structures are introduced, Old Bridge proved to have been correctly identified as being a key obstacle to flow in the River Avon and to be responsible for the elevated flood levels causing iundation of the city centre. Understanding the full effect of the Bath Flood Protection Scheme requires a complex hydraulic investigation, but as the effect of Old Bridge was very



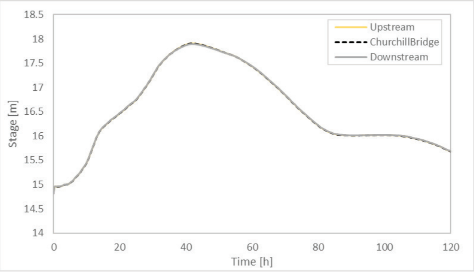


Fig. 6.7 Timeseries of stage during the 1960 flood for Old Bridge (left) and Churchill Bridge (right)

apparent in most historical floods in Bath, understanding the effect of this individual structure was an important part in the reconstruction of the historical flood events.

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7
TWERTON WEIRS

Twerton, also known as Twiverton on Avon, is a suburb of the city of Bath located to its west and home to Twerton weirs. As discussed in previous chapters, the city of Bath has a long history of flooding going back centuries. Phases IV & V of the Bath Flood Protection Scheme included the removal of the two weirs at Twerton and replacement by a twin automatic sluice barrage.

Twerton is considered a Saxon settlement on the River Avon but there is evidence that the village existed since the Roman times (THE BATH Magazine, 2020). It was considered outside the borders of the city until 1911, and was known for its mills milling corn and later cloth. The existence of the weirs is translated into the place name of “Twerton” which is derived from an Anglo-Saxon word meaning “Two Weirs” and illustrating the suburb’s riverside location (THE BATH Magazine, 2020).

At the beginning of the Industrial Revolution, the West of England was known for its wool textile manufacturing. Twerton had five mills located around the two weirs that were being leased (Fig. 7.1).

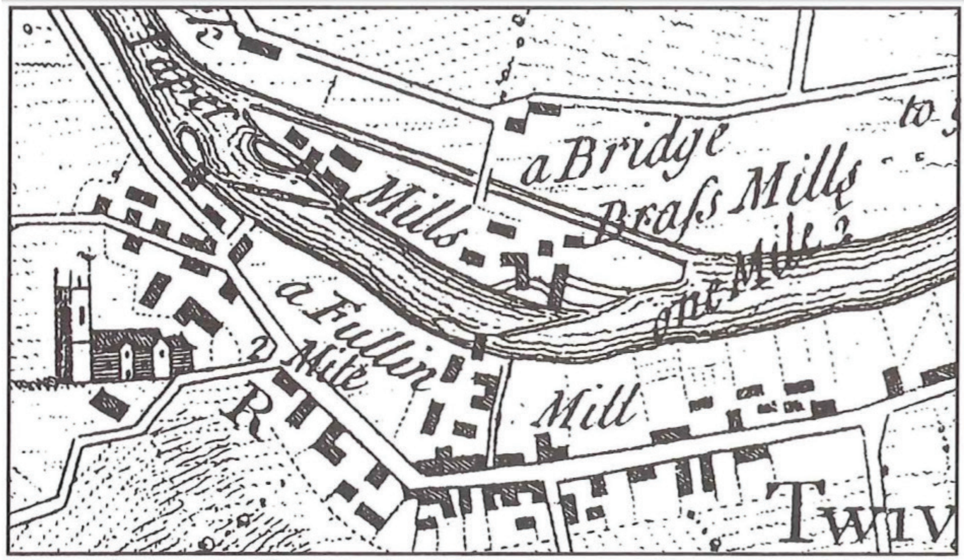


Fig. 7.1 Map of Twerton mill sites in the 18th century (Von Behr, 1996).

Engineering drawings of the two weirs dated 1934 were uncovered in the archives of the Environment Agency and are shown in Fig. 7.2. Twerton's manufacturing was therefore closely connected with the River Avon and the weirs. The first mention of a weir appears as early as 945 AD (Von Behr, 1996). Joan Day (1987) writes: "*Two adjacent weirs (Fig. 7.2) both served ancient fulling-mill sites on either bank of the Avon which here divides Weston and Twerton. Other diverse industries later occupied the sites, but the complex survived into this century mainly as large cloth-mill premises*". In the middle of the 16th century the Bath cloth industry collapsed, and by the 17th century the downstream mills were reverted to grist milling[1] (Von Behr, 1996).

In 1727 the Avon Navigation was completed, connecting Bath to Bristol for navigation via the river. During this time the Weston cut was created; a man-made channel on the north bank of River Avon created to allow boats to go through Weston lock (see map on page 8).

[1] A mill, especially one equipped with large grinding stones for grinding grain (Collins English dictionary, 1994).

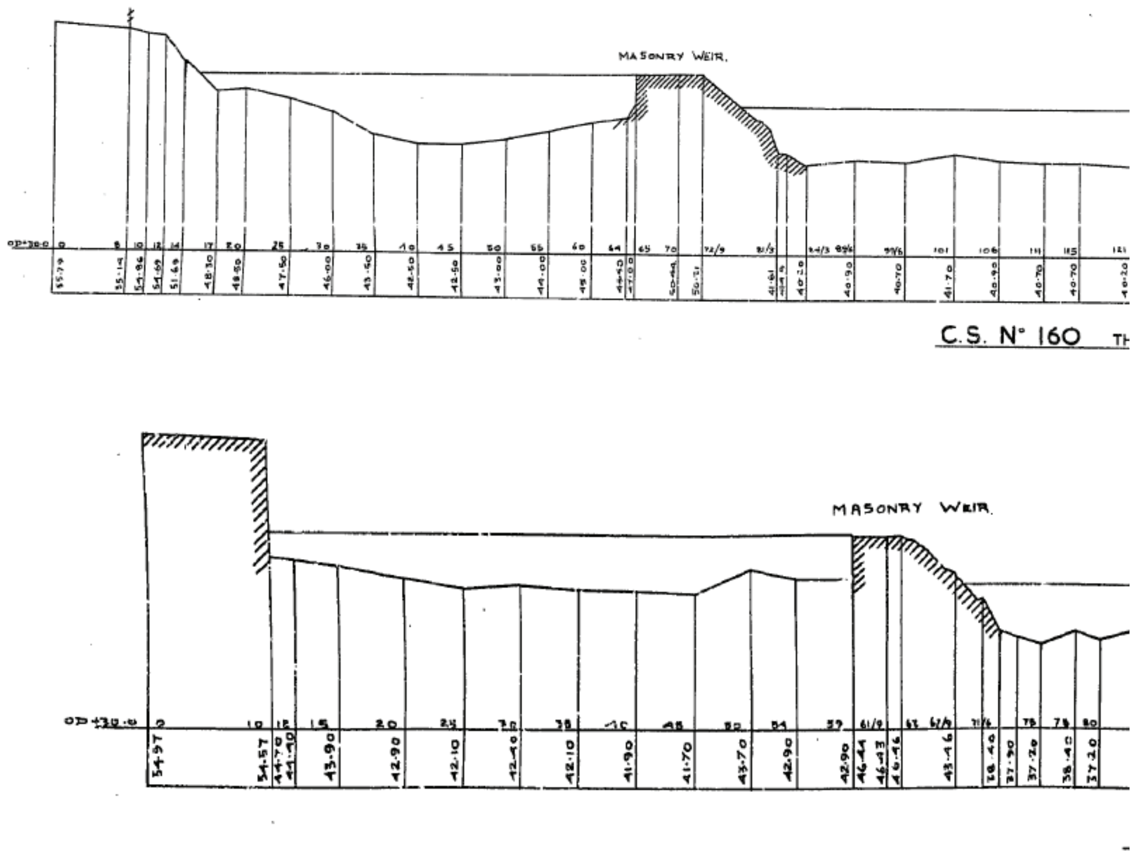
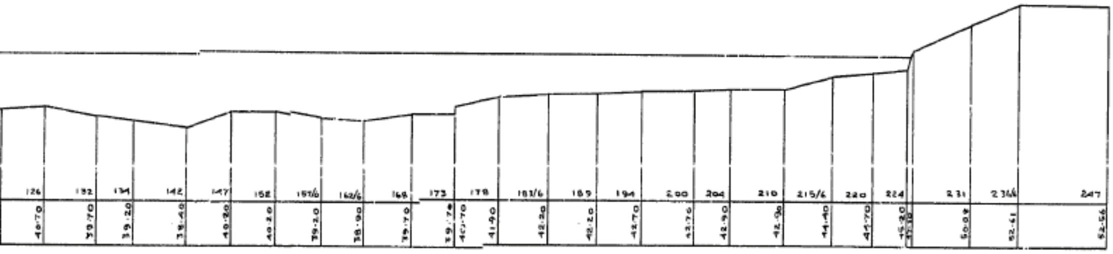
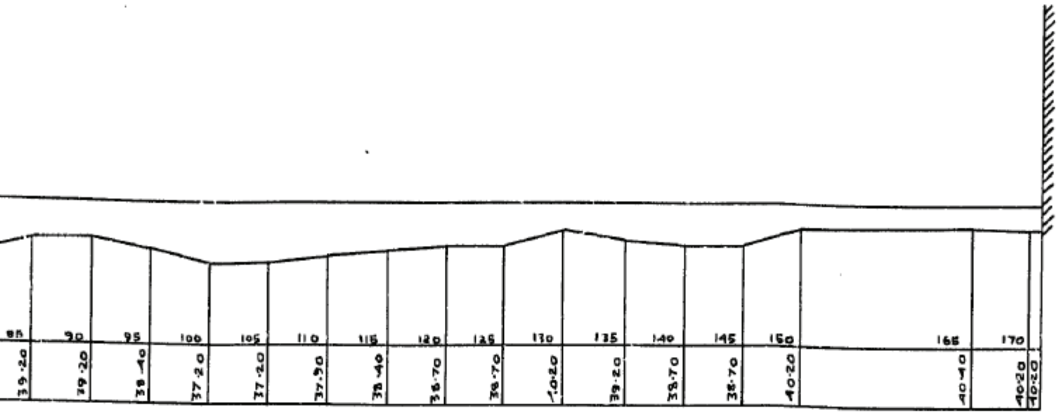


Fig. 7.2 Cross sections of upstream and downstream Twerton Weirs (from the Environment Agency's digital archives)



HROUGH UPPER TWERTON WEIR.



C.S. N° 155 - THROUGH LOWER TWERTON WEIR.

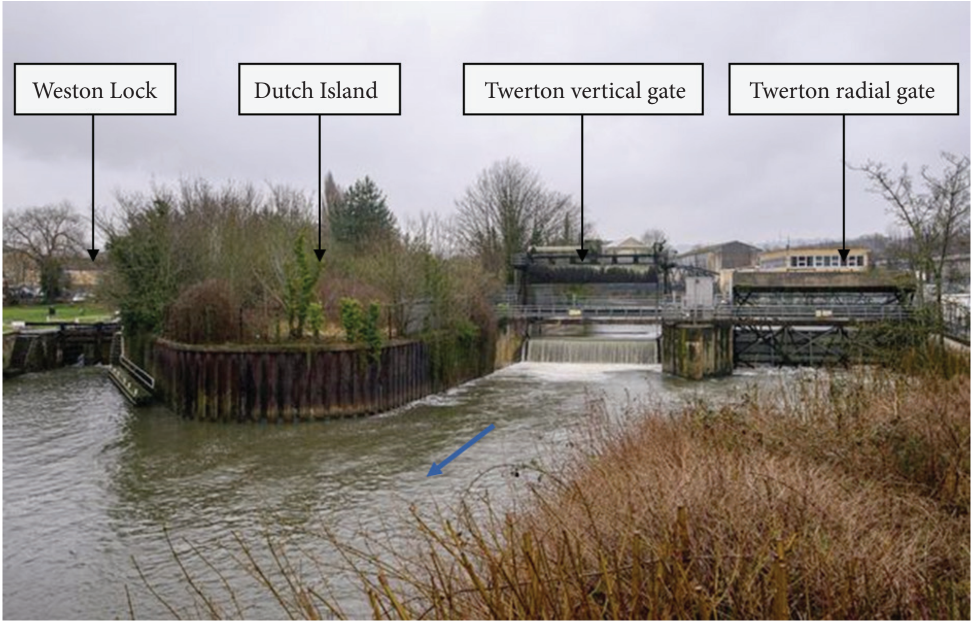


Fig. 7.3 Photo of twin gate system at Twerton looking upstream. The photo shows the Weston Lock, Dutch Island, Twerton vertical gate and the Twerton radial gate. The blue arrow represents the direction of the flow (Somerset Live, 2018).

Fig. 7.4 Modern day map showing the location of the twin gate system at Twerton (51°22′55.7″N 2°23′50.6″W)

Between the river and Weston cut, an island was created, Dutch Island (Fig. 7.3), which took its name from one of the brass mill owners (Allsop, 1989; Von Behr, 1996). The Weston cut left the existing Weston mills somewhat isolated on Dutch Island with a single footbridge access erected in 1728 (Day, 1987).

Phases IV & V of the Bath Flood Protection Scheme were completed in June 1968 (Greenhalgh, 1974) and the two weirs (Fig. 7.2) that stood at Twerton were replaced by a twin gate system (Fig. 7.3 and Fig. 7.4), a vertical and a radial gate spanning the length of the river (BATHNES, 2016a). The purpose of the modern gate system is to maintain the water level in the city centre within a viable range to: (i) facilitate navigation, and (ii) protect the historical World Heritage building foundations. Operation of the sluice gate is automated, and it opens/closes as required to maintain the required water level (BATHNES, 2016a). The usual water level range within the Twerton Gates Monitoring Station operates the gates is between 15.42 and 15.54 mAOD (River Levels, 2020). In October 2019, the Twerton radial gate got stuck open due to a fault causing the water level to drop by 0.8 m overnight and a further 0.1 m in the morning. The gate was fixed into its closed position and the levels were controlled by the remaining Twerton gate (Bath Echo, 2019). Fig. 7.5 below shows the data available from the River Levels database showing the minimum daily water level recorded between June 2019 and June 2020 including the extraordinary water level drop during the October 2019 incident.

The Bath & North East Somerset Council in their 2016 "Bath River Options Appraisal Report" discussed the possibility of replacing Twerton gates. It is recognised that these structures play an important

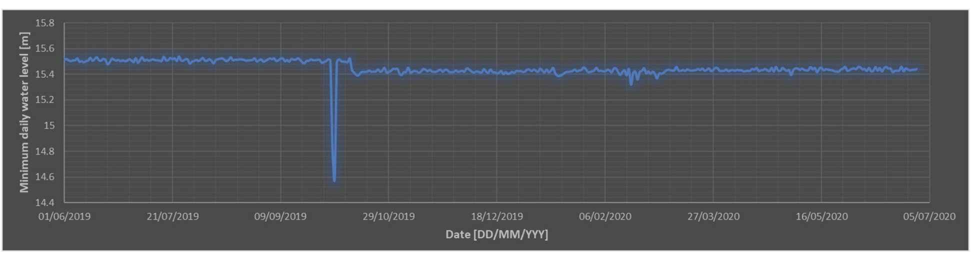


Fig. 7.5 Timeseries of minimum daily water level between June 2019 and June 2020 (Data from River Levels, 2020)

role in the flood risk protection of the city of Bath and are looking into many different options taking into account efficiency, economic benefits, environmental enhancements and climate change. The short-listed options that were considered in this report included: (i) do minimum, (ii) replace both gates and (iii) replace both gates with a variable height weir (BATHNES, 2016b).

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8
HYDRAULIC RECONSTRUCTION OF HISTORICAL FLOOD EVENTS

As detailed in the previous chapters the hydraulic characteristics of the River Avon has undergone considerable changes since the 19th century when the flood marks were left under Halfpenny Bridge. The changes were primarily a result of efforts to manage and reduce the flood risk in the city. For the purpose of reconstructing the historical floods, it was therefore key to conduct a detailed investigation of the hydraulic conditions existing at the time of these floods. As part of the HYDRIC BATH Project, this challenge was addressed by constructing a detailed hydraulic model of the river using historical data from a variety of sources. Using the Flood Modeller software, a hydraulic model was developed representing the stretch of the River Avon flowing from Bathampton, through the city of Bath and down to the Twerton weirs and predating the current Bath Flood Protection Scheme. Hydraulic models are a numerical representation of a river and are used as an investigation tool to understand a system's hydraulic behaviour. They can be useful for flood prediction, planning, catchment management, mitigation strategies, future infrastructure works and in this case for reconstruction of historical flood events.

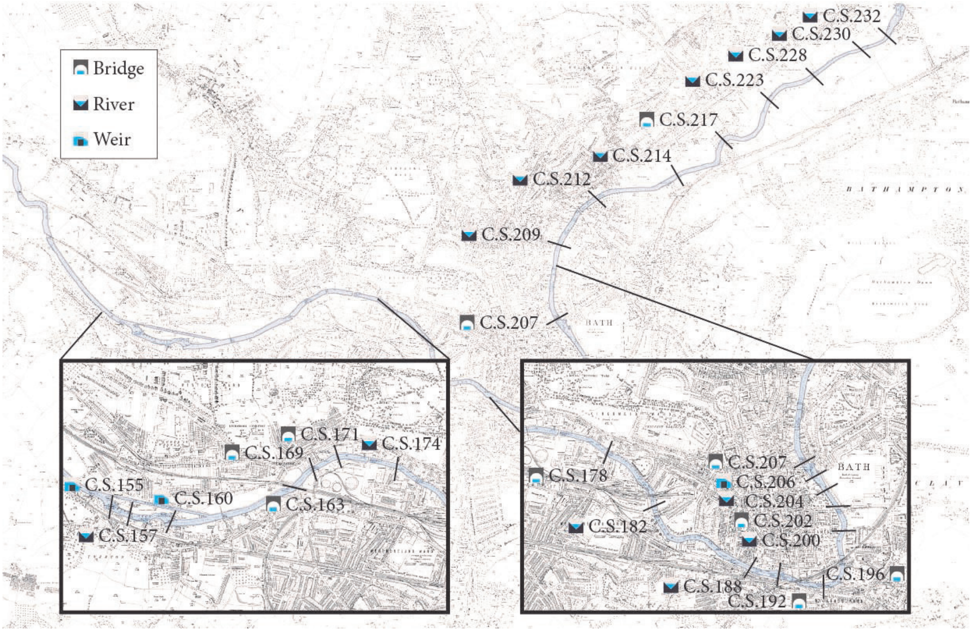

Fig. 8.1 Map of the city of Bath in 1904 highlighting the River Avon and the position of the river cross sections, bridges and weirs modelled in the hydraulic modelt

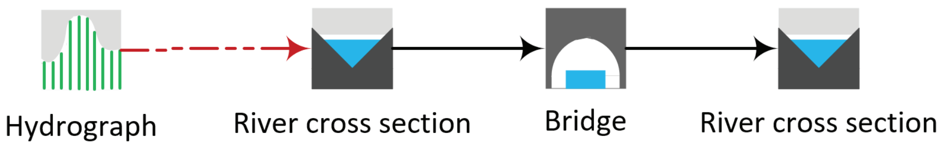

Fig. 8.2 Schematic showing a simplified setup with an input hydrograph, an initial river cross section, a bridge and another river cross section.

Building a historical hydraulic model is not an easy task and requires different aspects to be carefully considered. First, the river channel is separated into cross sections that represent the geometry of specific locations and are either simple river cross sections, bridges or weirs (Fig. 8.1). The longitudinal distance between the cross sections also needs to be specified. The schematic in Fig. 8.2 shows a simplified setup of a hydraulic model with an input hydrograph (the flow rate in the river over time) at the upstream end of the river, an initial river cross section, a bridge and another river cross section.

The first stage of the modelling process was therefore to create the hydraulic model for the River Avon and to achieve this it was necessary to obtain historical data of the river geometry and infrastructure at the time of the historical floods. The development of the model required river cross section data for the River Avon, historical maps, historical water levels and details of the bridges and weirs along the river's path. A historical map from 1904 was available from the Ordnance Survey showing details of the river geometry pre-Bath Flood Protection Scheme, and it was decided to create a hydraulic model covering approximately 8 kilometres of the River Avon from Bathampton Weir (cross section C.S.232) and down to Twerton Weirs (C.S. 155) downstream of the city centre of Bath.

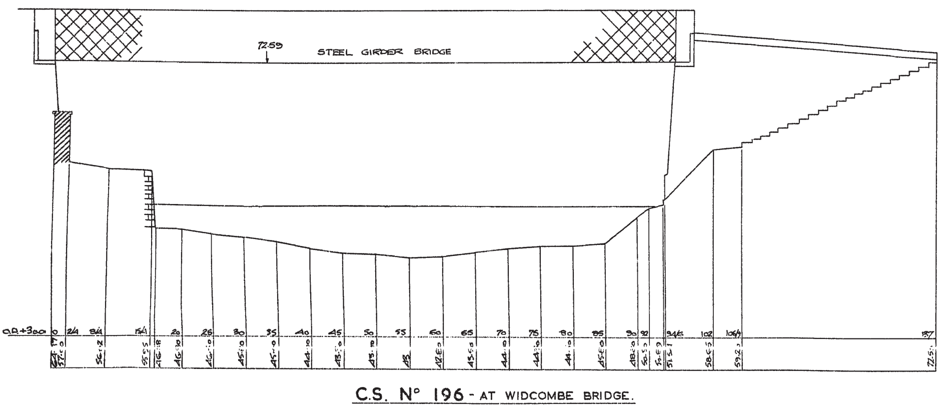

Fig. 8.3 Cross section containing details of Halfpenny (Widcombe) Bridge (from the Environment Agency's digital archives)t

A total of 54 individual river cross sections were used to construct the historical model. Engineering drawings of these cross-sections were found after extensive search in the Environment Agency's archives in the Bridgwater office, among another 1112 scanned drawings relevant to the Bath Flood Protection Scheme. The drawings were part of a longer survey of a total of 233 recorded locations which were measured in 1934 and replotted later to Newlyn Datums (the ordnance datum used as the basis for deriving altitudes on maps). An example of a cross section is shown in Fig. 8.3 containing details of Halfpenny Bridge, where the historical flood marks were recorded.

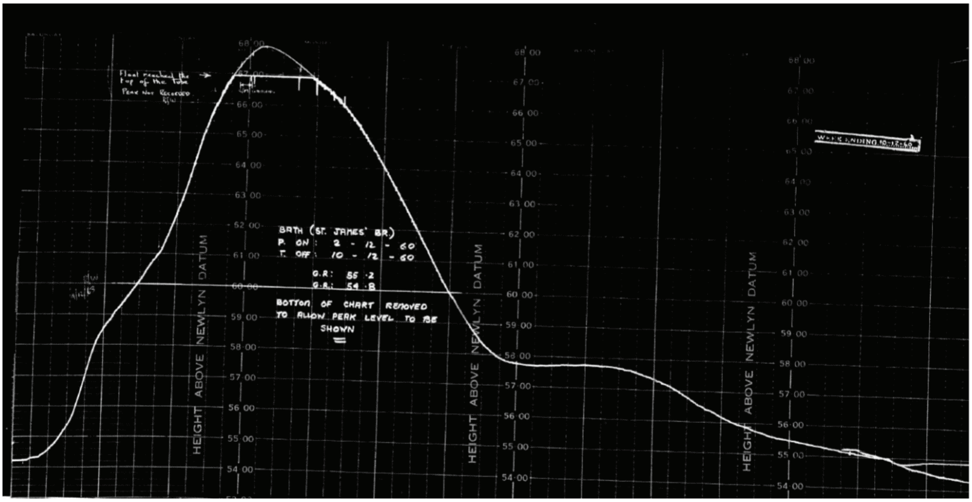

Fig. 8.4 Scanned hydrograph of the 1960 flood in Bath measured at St James' Bridge (from the Centre of Ecology and Hydrology's archives)

The creation of a realistic hydraulic model also requires access to reliable flood data and information. Flood hydrographs are graphs showing how a catchment responds to a rainfall event by plotting the flow rate over time for the duration of the flood. In hydraulic models, a hydrograph is introduced at the upstream boundary, in this case Bathampton, and then the model propagates the flood wave through the river network. To start the model reconstruction, a microfilm record of the water levels recorded during the 1960 flood was discovered in the archives of the UK Centre of Ecology and Hydrology in Wallingford. Fig. 8.4 shows the scanned hydrograph of the 1960 flood in Bath measured at St James' Bridge which is located 3.3 km downstream from Bathampton and 200 metres upstream of Pulteney Weir. As can be seen from the figure, the gauging equipment was overwhelmed shortly before the actual peak was reached but was subsequently filled-in at the time to provide a best guess of the maximum flow during the event.

An important step in the construction of the hydraulic model included digitising the 1960 hydrograph and all the river cross sections. The microfilm hydrograph for the 1960 flood was manually scanned, digitised and translated from water depth to flow rate using a rating curve (a graph showing the relationship between flow rate and water depth at a given point of a river). Following that all cross sections were also digitised manually from the PDF files and the units were converted from "feet" to "metres".

Starting at the upstream end of the river in Bathampton, the digitised 1960 flood event was defined as the inflow hydrograph at the top of the numerical model. Next, the different river cross sections were added and the distance between them and the channel roughness specified. Finally, all hydraulic structures were implemented (bridges, weirs) using the geometric data from the cross sections. Fig. 8.5 below shows the inflow 1960 hydrograph, two river cross sections and the representation of Old Bridge in the Flood Modeller software.

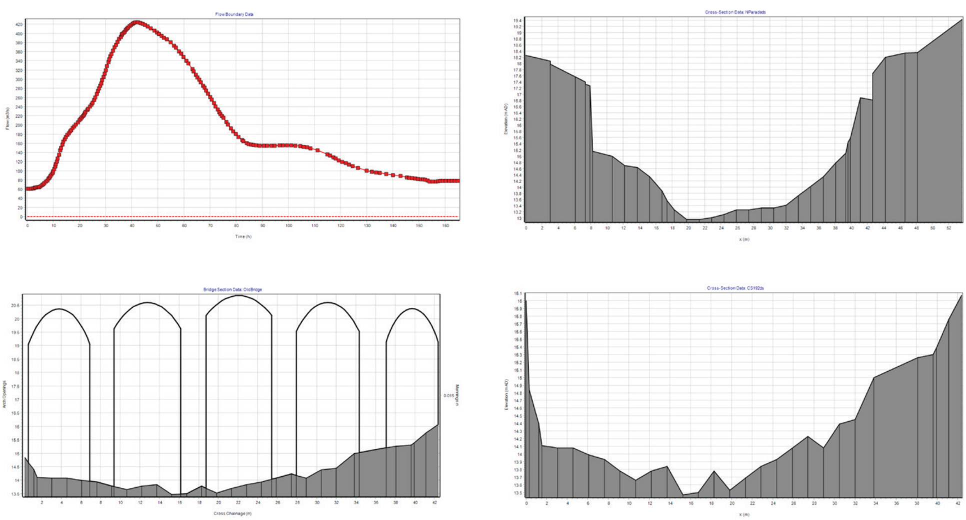

Fig. 8.5 Flood Modeller: 1960 hydrograph at Bathampton, Example river cross section 1, Old Bridge representation, Example river cross section 2

There are different outputs that can be extracted from the numerical model. Important and useful results in our research were the velocity, water depth or flow rate over time (hydrograph) at specific locations, including under the Halfpenny Bridge where the historical flood marks were recorded. It was also possible to visualise the results (as shown in Fig. 8.6) and examine the water depth evolution at a specific cross section (in this case at Halfpenny Bridge) over time during the 1960 flood.

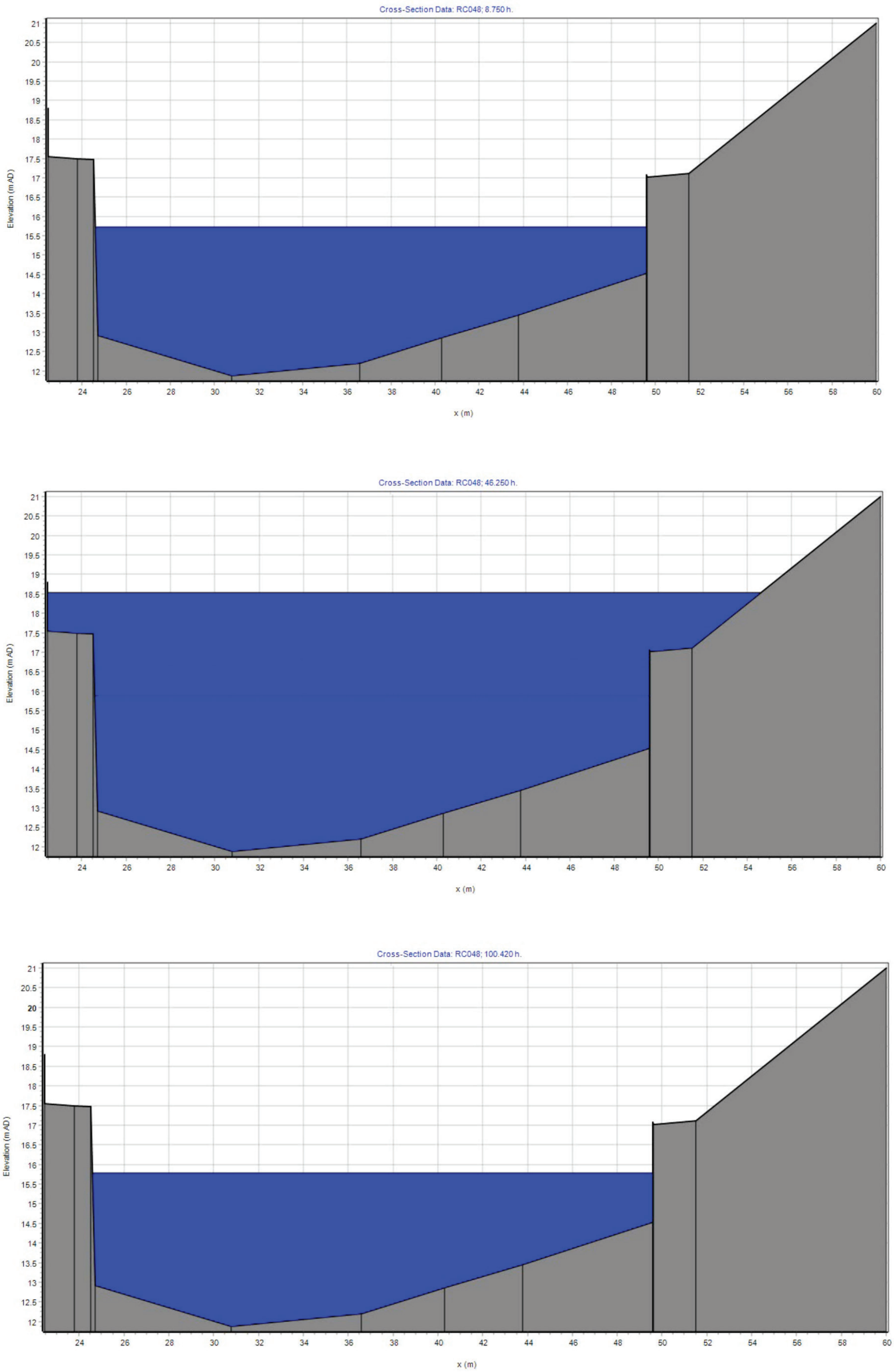

Fig. 8.6 Visualisation of results at Halfpenny Bridge during the 1960 flood event

Having separated the river channel into cross sections from section CS232 in Bathampton down to section CS155 located by Lower Twerton weir it became obvious that during all the historical flood events the floodplains around the river were inundated (which was also evident from historical pictures), an effect that was not represented accurately in our model. To further understand the hydraulic balance between the river and the floodplains of the catchment area, we started looking closer at historical photographs from the floods in Bath, mainly from the 1960, 1882 and 1894 floods. Using the Bath in Time online archive numerous photos of Bath during flood events were identified, which initiated the creation of our own interactive historical flood map containing historical photos from Bath in Time overlaid with the Environment Agency's historic flood map GIS layer showing the maximum extent of individual recorded flood outlines based on records from 1946. At this stage, the objective was not to investigate whether individual street or properties were flooded at the time of the events, but to understand the size of the different floodplains of the city. This allowed us to extend our cross sections to incorporate the effect of the floodplains into the hydraulic model. Fig. 8.7 shows River Avon Cross Section CS200 located about 150 metres downstream from North Parade Bridge. The continuous black line shows the river cross section obtained from an archived engineering drawing and the dashed black line shows the extended floodplains (calculated using the interactive map) towards the Dolomeads.

The final result of our interactive map is shown in Fig. 8.8 and is easily accessible by scanning the QR code present on the figure.

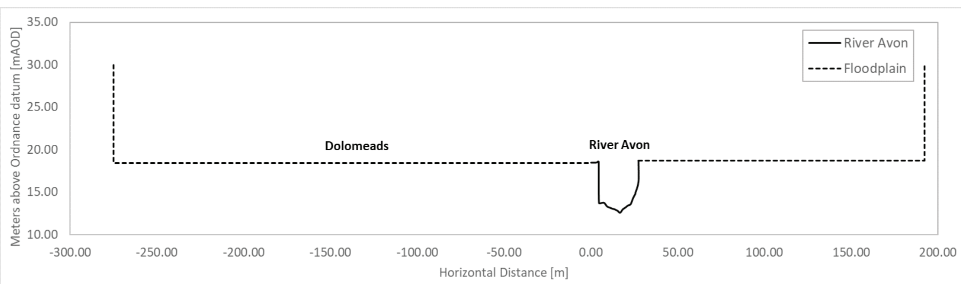

Fig.8.7 River Avon Cross Section CS200 and extended floodplains towards the Bath Cricket Ground and Dolomeads

Fig. 8.8 Interactive map with historical flood photos and flood extents (Bath in Time, 2020)

The legend on the left is separated in three categories:

1. Bath in Time Photos

The blue markers represent locations where we have historical flood photos from the Bath in Time archive. Press on the individual markers to navigate the photos. A description can be found below each of them as well as the link to the photo.

2. River Avon Cross Sections

The black star markers represent the River Avon's cross sections. Each of them marks the location of specific cross sections in the model where historical geometrical data was available and are either simple river cross sections, bridges or weirs.

3. Historic Flood Map

The historic flood map layer shown in blue, represents the Environment Agency's historic flood map GIS layer showing the maximum recorded flood extents around the river.

This allowed us to create a more detailed numerical reconstruction of the river and the changes to its hydraulic properties. The next stage of the reconstruction which will be described in the next chapter was to simulate the hydraulic conditions during selected historical floods (e.g. 1960, 1947, 1894, 1882) and using the historical flood marks at Halfpenny Bridge produce new modelled peak flows and compare them with the previously estimated flows.

SOURCES

Photos used in the flood map: Bath in Time, 2019 [Online]. Available from: https://www.bathintime.co.uk/
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9

A COMPLETE FLOOD RECORD FOR THE RIVER AVON

The aim of the research was to reconstruct historical floods for which a flood mark existed at Halfpenny Bridge – January 1866, March 1867, July 1875, November 1875, October 1882, November 1888, March 1889, 13th November 1894, 15th November 1894, February 1897, December 1900, February 1900, June 1903, January 1925, March 1947 and December 1960. The aim of the reconstruction was to ultimately result in a more accurate assessment of the peak flow of these events, which could potentially prove useful in understanding the contemporary flood risk facing the city of Bath.

After the detailed numerical reconstruction of the river and the changes to its hydraulic properties over the past two centuries, the parameters of the historical hydraulic model were calibrated to represent the river geometry pre-Bath Flood Protection Scheme (pre-1960). Calibrating a numerical model is a very important step in numerical modelling and involves adjusting some of the unknown model parameters within some acceptable uncertainty margins in order for the simulated model water levels to match some known measured values (e.g. a water level recording). Calibration is then followed by model validation, where the consistency of the model results is checked against measured values not used in the model calibration; i.e. validation is an independent check that the model gives the right results for the right reasons.

The first phase of the model calibration was a sensitivity analysis on Manning's *n* which is a coefficient representing surface roughness (where a lower value of n represents a smoother channel and a higher value a rougher surface). The sensitivity analysis of Manning's *n* investigates how changes in one variable (in this case Manning's *n*) affect the model output. From this, two different hydraulic models were built to provide the upper and lower threshold envelop of our results taking therefore into account the uncertainty in calibration values. The models were calibrated using inflow input from two more recent flood events where observed data were available (1947 and 1960 floods). The first model was calibrated using as input the microfilm version of the water levels recorded during the 1960 flood and the second model was calibrated using the maximum recorded water level at St James during the 1947 flood. The calibration was based primarily on adjusting the value of Manning's *n* of the main channel, but also an assessment of floodplain inundation based on evidence from historical photographs. The calibration resulted in a range of credible values of Manning's *n* which created our upper and lower threshold envelop.

The next stage of the research was to validate our recently calibrated model. Essentially, the only input parameter for the remaining historical flood events were the water level marks left on Halfpenny Bridge. For the model validation, three historical flood events were chosen where previous peak flow estimates existed in addition to the flood marks and these were the floods of October 1882 and 13th and 15th November 1894.

For each of the three events in turn, the peak flow of the inflow hydrograph (located at St James) was adjusted until an agreement between the simulated and observed water levels was obtained under Halfpenny Bridge where we had measurements for the height of the water levels. In all three cases, the peak flow estimates reported by others fell within the envelope provided from our numerical model which offered some confidence that the historical model was a credible representation of the main flood hydraulics of the river before the construction of the Bath Flood Protection Scheme.

Next, the remaining 11 historical flood events (for which historical water level marks existed below Halfpenny Bridge) were reconstructed using the two validated models following the same methodology; the peak flow of the inflow hydrograph was adjusted until a match was observed in the water level below Halfpenny Bridge. The outcome of the analysis was an upper and lower set of historical peak flow values which were then translated from St James (in the city centre) to Bathford (approximately 3 km upstream of Bath City) where flow recordings were initiated in 1969. All historical peak flow values were finally incorporated in a composite annual maximum series of peak flow consisting of data from 1866 to present day (Fig. 9.1).

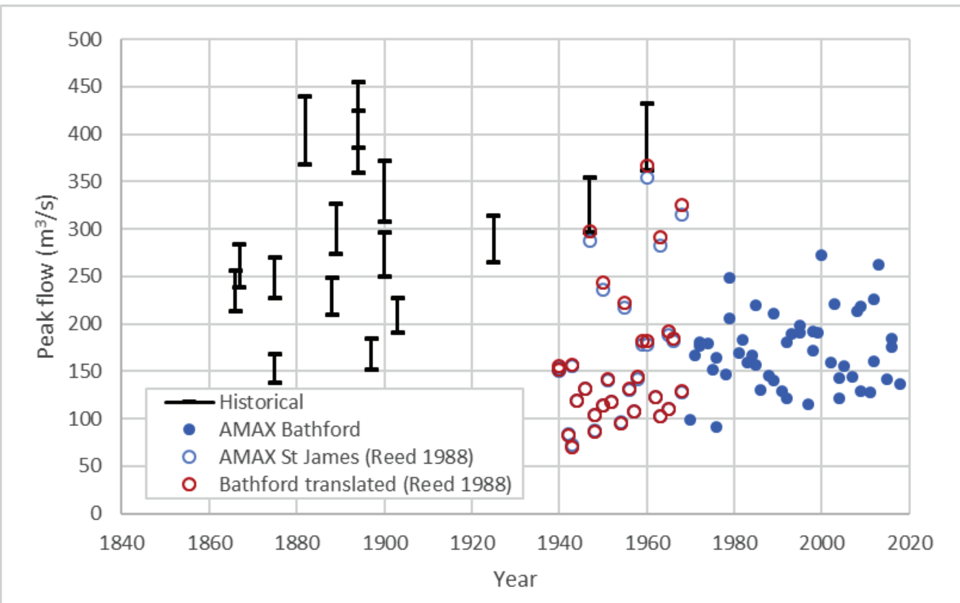

Fig. 9.1 Gauged AMAX flow series at Bathford station (1969-today) and AMAX flow series at St James station (1939-1968) (Reed, 1988) and translated to Bathford using the relationship found from our numerical model. The AMAX series at Bathford is therefore extended using the translated values from St James' station and the modelled historical floods with upper and lower envelope threshold for the River Avon at Bath, United Kingdom.

It is noticeable from Fig. 9.1 that modern data (post 1970) have not captured a flood peak with a magnitude comparable to some of those reflected in the historical data.

This research showed that the approach to the historical peak discharge calculation presented was successfully applied and was effectively used to augment an already existing annual maximum series of peak flow. This potentially allows an assessment of long-term trend or shifts in flood risk of the city and paves new avenues towards the inclusion of historical peak flows in future quantitative flood risk assessments.

10
CONCLUSION

The aim of the HYDRIC BATH Project was to reconstruct the hydrological and hydraulic conditions of significant historical flood events on the River Avon in the city of Bath. As demonstrated in this book, there is a wealth of historical information from multiple sources that, when compiled in a systematic manner, tell a fascinating story of past flood events and how efforts to combat future floods have shaped the city of Bath and the river environment as it appears today. The particular emphasis of this project was to bring the hydraulic and hydrological aspects of these historical flood events back to life. Various river authorities have been systematically monitoring flow in the river at two different locations from 1939 to the present day. The first flow measuring station was installed in 1939 at St James Parade (just upstream of Pulteney weir) and operated until 1969. As part of the Bath Flood Protection Scheme this gauging location was discontinued, and a new gauging station was installed at Bathford where the main west coast train line crosses the River Avon. This gauging station has been operating continuously from 1969 to the present day. Flood peak data recorded from these two gauging stations provide valuable insight into the magnitude and frequency of flooding of the river. However, research has shown that prediction of future extreme floods is notoriously uncertain. This uncertainty is further exacerbated by the changes to the river geometry and management resulting primarily from the implementation of the Bath Protection Scheme, and the general development of the city. One recognised route to reducing these uncertainties is to extend the time horizon of the flood data by reconstructing historical events from before the onset of systematic flow gauging. Nonetheless, as detailed in this book, reconstruction is a complicated process which requires access to historical information which is not always readily available, or available in the format required by the standards of modern hydraulic engineering.

During the project, the peak flow from a total of 16 historical flood events was reconstructed. A comparison between the peak flow of these events, and the largest flow value recorded in each of the years (annual maximum, or AMAX) between 1939 and 2020 was shown in Fig. 9.1. Note that the historical events are represented by an interval rather than a point, reflecting the level of uncertainty involved in the reconstruction efforts. The data show that the peak flows reached during the historical flood events appear in many cases to have eclipsed the maximum flood peaks experienced since the 1960 flood. However, there appears to be no modern equivalents in the flow data systematically recorded form the late 1960s onwards.

Climate change is widely expected to increase flood risk in the future, and research conducted at the University of Bath has shown that there are already clear signs that flood records in the West and North of the United Kingdom have increased over recent decades (Prosdocimi et al., 2019). The historical data in Fig. 9.1 demonstrate, on the one hand, that past generations observed flood events of a magnitude not seen since the construction of the Bath Flood Protection Scheme, yet, on the other, that the river appears capable of producing events not seen in modern times. Today, more than ever it is important to pave new routes and rethink flood management strategies in order to live in harmony with floods; neither be at odds nor overwhelmed by our natural environment.

SOURCES

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ABOUT US

DR IOANNA STAMATAKI

Dr Ioanna Stamataki is lecturer in the Civil Engineering Department of the University of Bath and worked as a Research Associate for this project. She received her Civil Engineering degree (MEng Civil Engineering) from the University of Bath, in 2014, and during her degree, she completed a dissertation on a hydraulics-based project involving the study of flow over complex weirs and used Pulteney Weir in Bath as her case study.

She continued into completing successfully a PhD at the University of Bath entitled "Experimental and numerical investigation of flash floods and their interaction with urban settlements". Following this, Ioanna worked a Research Associate in the HYDRIC BATH Project and investigated and assessed the utility of documentary evidence of past flood events with contemporary flood risk assessments in Bath.

Her expertise lies in the analysis and modelling of extreme events such as floods through laboratory experiments and CFD modelling. Ioanna has led and contributed to various outreach activities and participated in several initiatives for disseminating research to the general public.

DR THOMAS KJELDSEN

Dr Thomas Kjeldsen is senior lecturer at the University of Bath and was the project lead for this project. He is trained as a civil engineer (MSc, 2001; PhD, 2002) from the Technical University of Denmark, and has 15 years research experience focusing on mathematical and statistical modelling of hydrological and environmental systems, with particular emphasis on extreme events and sustainable use of resources.

He has led the development of the current UK industry standard methods for flood frequency analysis and hydrological design. Recent research projects include studies of the effect of urbanisation on catchment hydrology, development of a statistical extreme value procedure for regional and non-stationary analysis of flood events, and the use of local data in flood frequency estimation, including historical flood data.

From 2010-2014 he was chair of the pan-European COST Action ES0901 European Procedures for Flood Frequency Estimation (FloodFreq) involving more than 100 participants from 26 European countries.

DR CHRYSOULA PAPACHARALAMPOU

Dr Chrysoula Papacharalampou is the Executive Director of the Erasmus Research Institute of Management (ERIM), at Erasmus University Rotterdam, The Netherlands and worked as a Research Associate for this project.

Her expertise lies in the area of integrated water resources engineering and water policy, whilst her doctoral research (University of Bath, 2017) introduced an innovative systems approach for asset management practices. Her main research interests include socio-hydrology and system dynamics.

She has co-led and managed the 'River is the Venue' project, which aimed to engage the communities of Bath with the historic links between the flooding on the River Avon over the last 200 years, through active participation and using accessible public artworks. The project has received a Creative Bath Award in 2019 and has been shortlisted as a finalist for the Bath Life Awards in the Environmental Category in 2020.

CREDITS

This publication has been produced in an edition of 200 for the "Flooding through the ages: the city of Bath" lecture, part of the 2020-2021 Minerva Lecture Series, 2nd December 2020.

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The City of Bath is a historical UNESCO world-heritage site and is an instructive case study in how the history, architecture and development of a city can be closely connected to the city's relationship with its river, the River Avon. As the City has always been located close to the river, communities in Bath have experienced the effects of flooding since the Roman times. Bath has a particularly rich record of historical evidence left on buildings in the City (the earliest flood mark dates back to 1823) as well as documentary evidence in contemporary newspapers and technical reports.

This book hopes to take you on a journey of flooding through the ages. Starting from some important historical flood events and the multiple efforts of the City to combat the scourge of flooding, Dr Ioanna Stamataki and Dr Thomas Kjeldsen describe the different phases of the current Bath Flood Defence Scheme and discuss how historical flood events from 1823 to 1960 in the City of Bath were reconstructed using a 1D hydraulic model. This research area, drawing from the combination of the use of historical documentary evidence and modern technological modelling techniques, allows an assessment of long-term flood risk of the City and paves new avenues towards future research.

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