LLOYD'S

GEOMORPHOLOGY AND CHANGING FLOOD RISK IN THE UK

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1 EXECUTIVE SUMMARY

1. **RIVER CHANNELS AND FLOODPLAINS IN THE UK ARE DYNAMIC.** They respond to changes in the frequency and magnitude of floods and to variations in the size and volume of sediment transported. They can and do change rapidly with sometimes catastrophic consequences for businesses, communities and farms.

2. **INCREASING MODELLING EVIDENCE SUGGESTS FLOODING CAN BE ATTRIBUTED TO ANTHROPOGENICALLY DRIVEN CLIMATE CHANGE.** Although the landscape change signal[i] is not yet evident, geomorphic activity[ii] rates in UK rivers are likely to increase. Climate modellers predict increasingly frequent heavy rainfall events, especially in winter, leading to more flooding in the UK.

3. **MORE THAN 30 MAJOR RIVERS IN THE UK HAVE EXTENSIVE REACHES THAT ARE CURRENTLY OR WERE HISTORICALLY, MULTI-CHANNEL. THESE RIVERS REPRESENT SIGNIFICANT VULNERABILITY POINTS IN THE RIVER NETWORK TO INCREASED FLOODING.** Channel evolution can be traced using O.S. maps, vertical aerial photography and remote sensing imagery in Geographical Information Systems. This can help planning authorities and environment agencies to identify potential points of vulnerability.

4. **THE REACTIVATION OF FLOODPLAIN SEDIMENTS CONTAMINATED BY HEAVY METALS IS AN EMERGING RISK ASSOCIATED WITH RIVER FLOODING IN THE UK.** Prompted by the widespread pollution of many previously mining areas of northern England, following the Autumn 2000 floods, a series of risk assessment and management protocols have been developed to try to identify potential hazard zones.

5. **NEW METHODS OF EXTENDING THE FLOOD RECORD HAVE SHOWN THAT RECENT DAMAGING FLOOD EVENTS ARE NOT UNPRECEDENTED, BUT OCCURRED MORE FREQUENTLY IN THE PAST.** Current long term flood records are limited. One of the primary challenges for river scientists in the UK is to find alternative methods of extending the flood series to establish if floods are becoming more frequent and/or larger and establish the impact of climate change. Two principal methods of extending flood records have emerged: the use of documentary sources and the sedimentary archives of floodplains

6. **CLIMATE RESILIENT APPROACHES TO FLOOD RISK ASSESSMENT NEED TO BUILD ON AN ASSESSMENT OF PAST AND PRESENT FLOODPLAIN AND RIVER DYNAMICS.** This will allow insurers and other policymakers to identity areas where river corridors are vulnerable to future flooding. Targeting resources at sites most at risk is also a more economically and environmentally "sensitive" way of handling flood risk management.

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[i] A signal is a visible reponse of a system to a defined input.
[ii] Geomorphic activity refers to processes and changes in landforms

2 INTRODUCTION

Although the changing nature of rivers are well known by geomorphologists, it is largely unappreciated by many people in the insurance industry who have tended to view rivers in the UK, especially heavily engineered systems in urban and lowland contexts, as fixed in size, form and position. However major flood events in the UK over the last decade, including the 'Millenium Floods' of Autumn 2000, Boscastle in August 2004, the Summer floods of 2007, and those in Cumbria in November 2009 have radically changed this perception, demonstrating that rivers are not passive backdrops to the business, industrial, urban and agricultural use of floodplains. River channels and floodplains can and do change rapidly with sometimes catastrophic consequences for communities, farms and industry.

With climate modellers predicting more flooding in the UK, the rates of river bed and bank erosion and floodplain sedimentation are also likely to accelerate.What is also becoming increasingly clear is that it is not always environmentally or economically prudent nor practical to exclusively focus efforts on engineering solutions to flooding problems caused by the encroachment of properties onto floodplains, and potentially made worse by climate change. A more informed way of using geomorphological science and data is required that identifies those sites most at risk and targets our increasingly limited resources at these areas. This is a new way of thinking and should be considered as additional and complementary to the more traditional, 'hard' engineering approaches to flood defence.

The principal aim of this report is to examine the current research agenda as it relates to *vulnerability points* in river systems, and to make recommendations where future research and resources may be most useful and which the insurance industry should prioritise.

Three emerging areas of geomorphological research are discussed in this paper. They will have a significant bearing on how the insurance industry, local authorities and the environmental protection agencies assess and manage future flood risk in the UK. They are:

1. Historical *river channel pattern changes*, including the changing nature of 'natural' channel dimensions (bed levels and channel capacity), and how they can alter in response to variations in the magnitude and frequency of flooding.

2. The distribution of *polluted floodplain sediments* arising from former mining and industrial activities, which are vulnerable to reactivation and pose a significant risk to ecosystems and human health.

3. Detection and attribution of *environmental signals*[iii] *in flood records* associated with climate and land-use change.

The report will also outline the potential use of a number of new methodologies to better assess flood risk. These include:

- *Geographical Information Systems, data processing and archiving procedures* of river channel position and pattern change. Alongside appropriate future flood estimates based on climatic and hydrological forecasts, these would allow a national-scale risk assessment to be considered for planning purposes

- *Sediment based flood records* derived from the analysis of floodplain sedimentology, independently dated to extend the flood series.

[iii] Envirionmental signals are environmental changes that can be attributed to climate change or land-use change such as a change in sediment transported in a river.

3 CLIMATE CHANGE AND FLOODING

The next Assessment Report (AR5) of the UN Intergovernmental Panel on Climate Change is due out in mid-2013 and is likely to reinforce the conclusions of the previous four assessment reports, which showed that human-induced global warming has altered the climate beyond what can be considered natural variability. Past research has traditionally focused on the implications of continued warming on natural and biological systems, and the effects that climate change will have on social and economic systems.

While detection and attribution studies are well established for a range of climate and impact metrics, the attribution of geomorphological events such as landslides and river floods is in its infancy. In many cases, the landscape change signal in response to contemporary climate change is not yet evident. Of increasing concern to insurance markets and policymakers is whether river flooding can be attributed to anthropogenically-driven climate change. Increasing evidence suggests that this link can be made.

1. There are strong thermodynamic and hydrodynamic reasons why precipitation and flooding should increase in a warmer world, including concentrations of water vapour in the atmosphere[1].
2. Such increases in precipitation have been observed throughout the twentieth century[2], although the links between precipitation and flooding are partly obscured by other factors such as changes in land use.
3. IPCC Global Climate Models (GCMs) point to increases in precipitation intensity for the remainder of the century[3]. Assessment of model projections suggest that precipitation will increase globally by around 1.7% per °C rise in temperature, with an increase in intensity of around 2% per °C rise[4]. As a result, policymakers should expect an increase in flood events.
4. Recent advances in modelling flood events have, for the first time, shown that twentieth century greenhouse gas emissions have increased the risk of flood events[5]. However, such analyses have only been achieved for specific floods (in this case the major floods that affected parts of England and Wales in 2000).

Flood risk management faces two challenges: a changing climate that will alter patterns and frequencies of inundation, and an economic climate that is likely to prevent extensive public expenditure.

In addition, changes to many natural systems relate to thresholds at different levels, which may be below the political climatic-change targets currently seen as achievable. Many of the *impacts* of climatic change are local and national, and this is where informed forecasting and public understanding are essential if people and property are to be protected.

4 CLIMATE CHANGE AND UK RIVER DYNAMICS

Changing experience of floods and droughts in the UK may help galvanize public opinion about environmental change. Flood risk is not completely avoidable, but may be mitigated in different ways, including engineering works, planning controls and building regulations, insurance, warning and emergency intervention, and rescue. The current economic climate means that high cost solutions can only be afforded for the most vulnerable sites, making it necessary to identify areas most at risk and to inform public authorities, agencies and vulnerable property owners about the risks they may face. Understanding how the climate interacts with river dynamics is crucial in understanding and identifying these risks.

River channels and floodplains in the UK are dynamic, responding to changes in frequency and magnitude of floods, and to variations in the size and amount of sediment they transport. Changes in river flow are primarily controlled by climate-related variations in precipitation. However, how the land is used within river catchment areas and the type of land cover strongly influences runoff rates and water storage. River channels can move hundreds of metres within a few decades and, in some instances, tens of metres or more during a large flood event. Over similar time periods, rivers can also erode or fill their channels with sediment to a depth of 1-2 metres. Rivers are not passive backdrops to the business, industrial, urban and agricultural use of floodplains.

Geomorphic activity rates (river bed and bank erosion and floodplain sedimentation) in UK Rivers are likely to accelerate. Climate modellers predict an increasingly frequent number of heavy rainfall events, especially in the Winter[6], leading to more flooding in the UK. To avoid the resulting greater economic and environmental costs and additional personal injury, these scenarios must be fully and effectively incorporated into future flood risk assessment and management strategies.

5 RIVER CHANNEL PATTERN CHANGES AND FLOOD RISK

5.1 GEOMORPHOLOGICAL CHARACTERISTICS OF UK RIVER CHANNELS AND FLOODPLAINS

River channels and floodplains in the UK can be classified into four categories – braided, active meandering, inactive meandering and anastomosing (Figure 1). This is based on research of river discharge gradient, bed material and the amount of sediment in rivers.

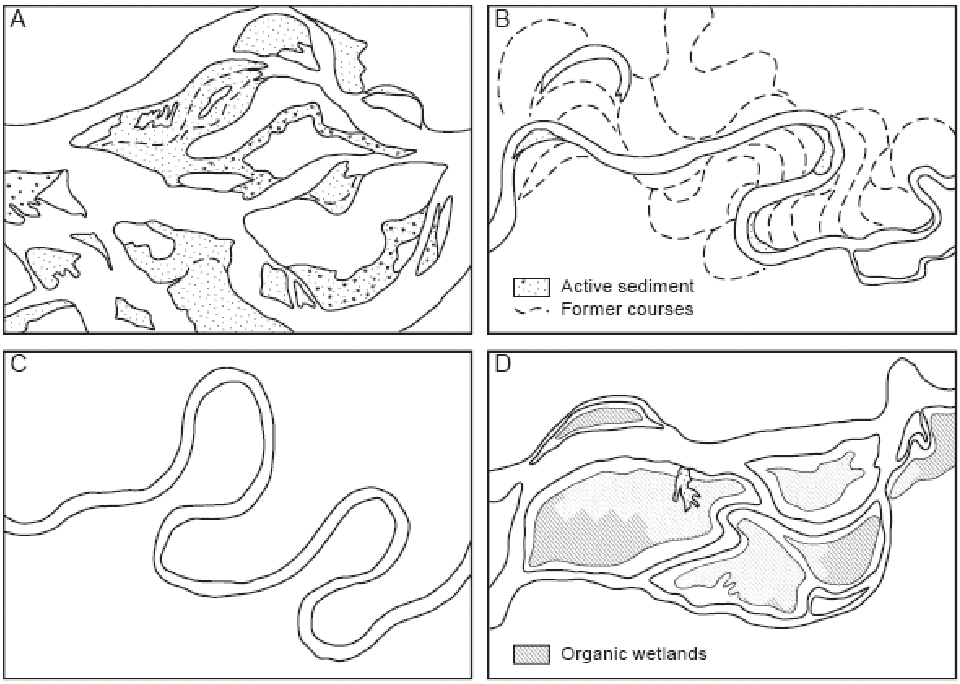


Figure 1: UK river channel and floodplain styles: (A) braided, (B) active meandering, (C) inactive meandering, (D) anastomosing[7].

Each of these rivers has different channel movements, with significant and varying impacts on the extent and pattern of both current and future flooding. Importantly for flood risk assessment and management, each river channel and floodplain style has a characteristic and generally predictable pattern of development. These river channel and floodplain types have also historically responded in a consistent way to climatic fluctuations and to changes in river catchment land-use, by adjusting their channel morphology to cope with the varying water volumes and sediment loads. Assigning sections of rivers to one of these four channels and floodplain styles provides a useful starting point for forecasting the likely impacts of future environmental change on UK floodplains[8].

In most UK catchments these river channel and floodplain styles change down-valley as gradient and stream-power decline and sediments become finer. The changes tend to follow this sequence: braided → active meandering → inactive meandering → anastomosing (Table 1).

TABLE 1: REPRESENTATIVE DIMENSIONS (WIDTH/DEPTH RATIOS), GRADIENTS OF CHANNEL BEDS (GRADIENT), SPECIFIC STREAM POWER AND BED MATERIAL FOR PRESENT-DAY UK RIVER CHANNELS[9].

	Width : Depth Ratio	Gradient/Specific Stream Power[iv]	Bed Material
A. Braided	>20	>5 m/ km^{-1}, >100 W m^2	gravel
B Active meandering	5-20	>2 m/ km^{-1}, 10-100 W m^2	sand/gravel
C Stable meandering	<15	<3 m/km^{-1}, 50 W m^2	sand/gravel
D Anastomosing	<15	<2.5 m/ km^{-1}, <20 W m^2	sand/gravel

[iv] Stream powers refers to the energy available to transport sediment.

Braided river channels are now rare in the UK and are presently found only in upland valleys; particularly in Scotland, Wales and in some parts of northern England (see Table 2). Historically, braided channels were also common at the margins of upland areas where valleys widen abruptly and steeper tributary streams join lower gradient main rivers. They are characterised by high stream power that enables them to transport gravel and coarser size bed material. They also have multiple active channels, whose position can shift by 10-100 m or more during a single flood event. Flood defence is notoriously difficult to manage for braided rivers.

TABLE 2: CONTEMPORARY RIVER BRAIDING IN BRITAIN[10].

River	Catchment Area (km^2)
Feshie, Highlands	235
Spey, Grampian	2850
Nent, Cumbria	25.6
Carlingill, Cumbria	2.6
West Allen, Northumberland	50
South Tyne, Northumberland	800
Harthope, Northumberland	N/A
Langden Brook, Lancashire	15
Bollin-Dean, Cheshire	N/A
Dane, Cheshire	152
Ystwyth, Dyfed	193
Tywi, South Wales	747

Active meandering river channels are also characteristic of upland valleys in the UK. However, they also extend into lowland environments along rivers such as the Bollin (a tributary of the River Mersey in NW England), Swale (Yorkshire), Tees (County Durham and North Yorkshire) and Ure (North Yorkshire), as well as catchments fringing the Cambrian Mountains. National surveys of river channel movement in England and Wales show that most of the changes are concentrated in the margins of the Pennine and Welsh uplands[11],with almost 35% of the rivers draining upland England (including Dartmoor and Exmoor) showing some pattern instability during the last 100 years. Active meandering channels transporting gravel-size sediment can erode their banks locally by 1-10 m per year. During floods, they can also periodically straighten their course by cutting off former meandering channels.

Inactive meandering rivers are those that have remained in approximately the same position for the last 150 years. They are common in the UK lowlands. However, radiocarbon dating of organic material from bordering relict channels (termed palaeochannels), shows that inactive meandering rivers were more active in the past during periods of wetter climates[12]. The stable position of many UK rivers, especially in lowland areas, is evident in their heavily-vegetated banks and in the occasional survival of ancient buildings. There are a range of different inactive channel types in lowland UK but most are either tree-lined and gravel bedded, or clay lowland rivers.

Anastomosing river channels were common in the UK lowlands prior to the Industrial Revolution and widespread engineering and infrastructure development on floodplains. Unlike their braided, high energy anabranching counterparts in northern and western UK, these multi-channel rivers have fine-grained and cohesive banks and are generally stable. Although usually found in tidally-influenced rivers in eastern and southern UK, new channels could be formed by floodwaters breaching naturally formed sandy levees and flowing into lower lying adjacent inter-channel wetlands (see Figure 1D). Many larger lowland rivers (see Table 3) in England, such as the Great Ouse and the Thames and its tributaries, had anastomosing channels until the 19th century. However, these were completely transformed by urban and industrial encroachment and the development of the railway and road networks. For example, the Lower Lea valley in London was extensively anastomosing as recently as 1746[13]. Multiple channels are still present in the area, fossilised by railway and industrial development (see Figure 2).

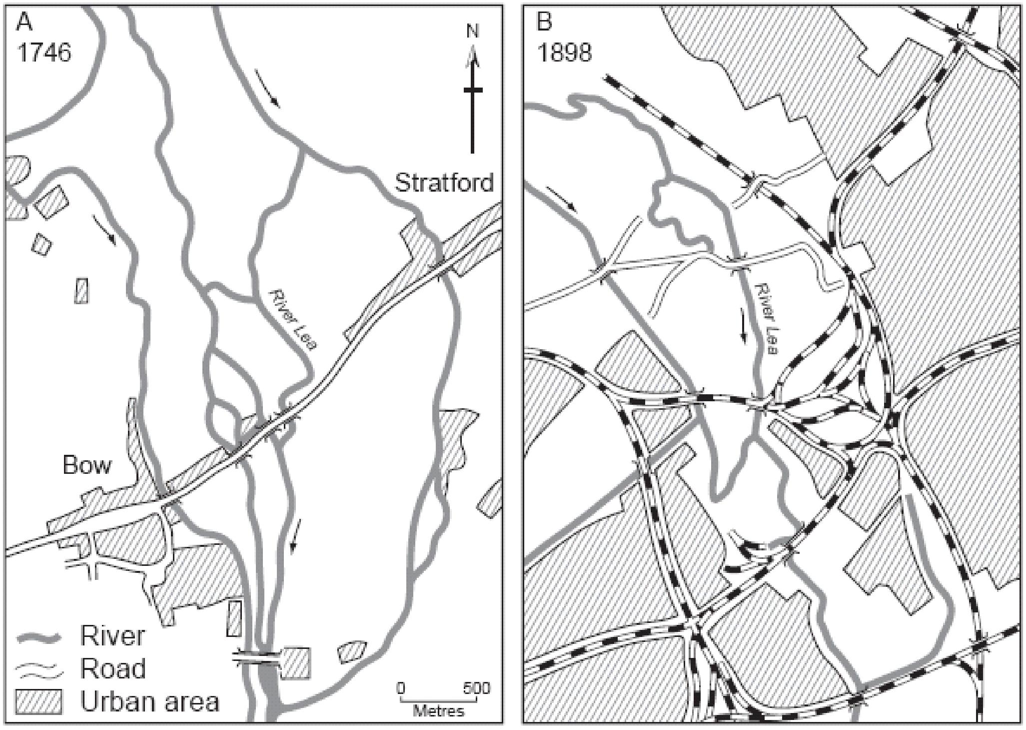


Figure 2: The anastomosing course of the River Lea in 1746 and 1898 showing the encroachment of urban, industrial and railway development onto the floodplain (the development of railways is illustrated by the hatched black and white lines)[14].

5.2 RISKS POSED BY RELICT RIVER CHANNEL NETWORKS

Historical multi-channel (anabranching) river channel networks, whether the braided or anastomosing type, are evident on many UK floodplains. During heavy rainfall, or when flood embankments (built to confine flows or to block and disconnect former anabranches) are breached, these rivers periodically carry significant flows from locally generated runoff. This occurs as these river systems have rainfall threshold responses (tipping points) which once reached causes the river channel to be reactivated. These rivers are significant *vulnerability points* for increased flooding. Nationally more than 30 major rivers in the UK (see Tables 2 and 3) including the Severn, Thames, Trent and Tyne, have extensive reaches that are currently or were historically anabranching and so could be at greater risk from flooding.

TABLE 3: HISTORICALLY ANASTOMOSING RIVERS IN ENGLAND[15].

River	Length of river channel between tributaries (km)[v]	Floodplain Width (km)	Gradient (m/km)
Upper Thames (Radcot-Carswell)	4.81	0.78	0.63
Thames (Wolvercote-Ifley)	7.25	0.5-0.96	0.55
Kennet (Reading)	c. 4.0	c. 0.7	Unknown
Lodden (Twyford)	2.53	0.34	0.79
Wey (Woking)	2.76	0.52	0.72
Colne (Denham-Staines)	15	0.72	1.0-1.45
Lea (Waltham Abbey-Blackwall)	27.5	1.26	1.14
Medway (Tonbridge)	5.3	0.41	0.94
Great Ouse (Huntingdon-St. Ives)	7.04	0.78	0.68
Nene (Northampton-Oundle)	35	0.42-1.02	0.41-1.6
Soar (Leicestershire)	3.4	0.5	1.4
Trent (Nottingham)	c. 7.0	2.8	0.3
Trent (Newark)	4.49	2.47	0.45
Itchen (Worthy-Eastleigh)	6.74	0.53	2.5
Test (Houghton-Dunbridge)	7.39	0.83	1.35
Exe (Cowley Bridge-Exeter)	3.71	0.34	1.35
Severn (Gloucester)	2.95	1.4	0.68

Channel evolution, both geographically and over time, can be traced using large-scale plans and maps. Changes in river positions, dimensions and planform pattern (number of channels, islands and bars) can be documented with uncertainties less than ± 5 m (see Figure 3), by digitising, overlaying and sequentially comparing O.S. map revisions, vertical aerial photography and more recently remote sensing imagery in Geographical Information Systems (GIS). These processes can help planning authorities and environmental risk agencies to understand and identify river dynamics and potential vulnerability points.

Information about the way river channels have changed from the 19th century up to the present day has been systematically compiled for the main rivers of Wales[16] along with parts of northern England, including the Tyne[17], Swale[18] and Dane[19] catchments. Current research has focused on these areas, suggesting further work needs to be conducted on the remaining regions of the UK.

[v] A tributary is a lower order stream which joins a main river. These tributaries join at various intervals and this measure refers to the distance down river between these tributaries.

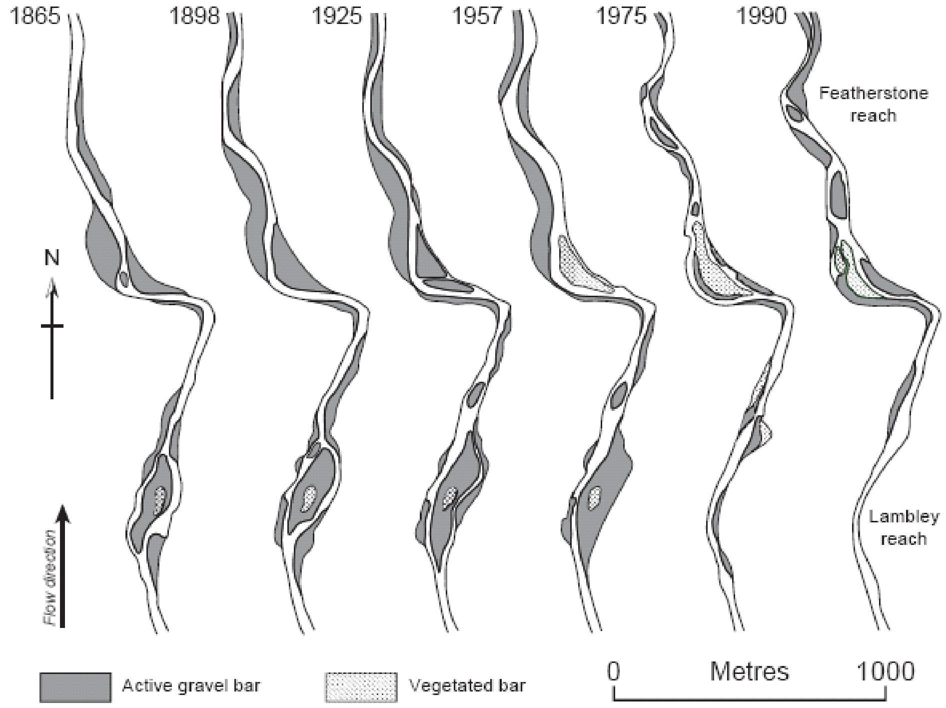


Figure 3: Successive maps of channel and sediment bar[vi] morphology at Lambley and Featherstone, River South Tyne, derived from cartographic and aerial photograph sources. This image shows how the channel and sediment bar has moved across the valley floor over time[20].

CASE STUDY

Historical maps and aerial photographs of the South Tyne and Tyne rivers spanning the period from the mid-18th century up to the present day, show more than 30 sites where river channels were formerly unstable and actively braiding[21]. In the 30-40 year period from the late 1950s until the mid-late 1980s all but three reaches stabilised and transformed into single thread river channels with significantly lower rates of bank erosion and lateral movement. New infrastructure (including bridges and road embankments) and housing developments encroached on the floodplains following reduced river mobility. An increase in flooding since the mid-1990s has resulted in widespread disruption and growing damage to new-build properties' infrastructure built on floodplains as the perception of flood risk had been incorrectly judged as low and decreasing.

A similar pattern of development is evident in the formerly anastomosing rivers of lowland UK, where recent flooding problems have been significantly exacerbated by reducing space for river flows rather than an actual increase in flood discharges since the 1990s (such as the River Lea in North London – see Figure 2). For instance, the Summer 2007 floods (which prompted the Pitt Review) reactivated formerly anabranching rivers such as the Don and its tributaries in Sheffield and the Trent and its now-urbanised tributaries in Nottingham. The 2007 floods devastated parts of South and East Yorkshire, Gloucestershire, Oxfordshire and Worcestershire, causing around £4 billion of damage, £3 billion of which was insurable[22].

[vi] A bar is an elevated region of sediment that has been deposited by the flow of the river

5.3 TOOLS FOR IDENTIFYING RIVER CHANNEL CHANGES

Since the creation of the British History Online web site[23], a digital library of many of the core printed sources for the medieval and modern history of the British Isles, it is now easier to compare maps and establish changes in river channel position and pattern. Ordnance Survey maps at a 1:2500 and 1:10,560 scale are now available online from the mid-late 19th century for the whole of Great Britain. Since early 2010, users can compare historical 1:2500 and 1:10,560-scale modern O.S maps on the same screen. It is also possible to view these historical maps alongside a modern satellite image of the same area.

Google Earth's historical image comparison facility also provides highly resolved spatial and temporal data on UK river dynamics at one to two year time intervals for roughly the last decade. These free and easy to use tools could help all relevant regulatory agencies and authorities to identify river reaches across the entire UK to find if there had been significant, relatively little, or no river channel movement or pattern change. This could then alert them to where local river channel and floodplain geomorphology are likely to significantly affect present and future flooding.

6 SEDIMENT-ASSOCIATED POLLUTANT DISPERSAL AND FLOODING

One of the unexpected consequences of the Autumn 2000 UK floods was the widespread dispersal of sediment-associated pollutants in floodwaters and their deposition on inundated land[24]. At the time, environmental managers and regulators failed to recognise that flood water can transport significant quantities of pollutants in a particulate form. Long-lived, heavy metal pollutants such as cadmium, copper, lead, mercury and zinc, which are harmful to both ecosystems and human health, are of particular concern.

The principal source of these pollutants in the UK is the historical metal mining and metal processing of the 19th and early 20th century. Metal-rich effluent was generally discharged into the nearest watercourse and at that time lack of adequate waste regulation resulted in widespread contamination of floodplains when they flooded. Although large-scale metal mining and processing in the UK ended shortly after World War Two, many floodplains in the former metal producing areas of northern and southwest England, north and mid-Wales and southern Scotland are still extremely polluted with heavy metals. These metals are present in concentrations that could potentially harm livestock which graze on the contaminated land. Unless costly remediation measures are carried out, such contamination can also prevent the re-development of metal contaminated floodplains both in rural and urban areas in former industrial cities such as Leeds[25], Manchester and Newcastle.

Prompted by the widespread pollution of many parts of northern England affected by historical metal mining during the Autumn 2000 floods, a series of risk assessments and management protocols have been developed and successfully tested in a range of UK catchments (see Figure 4)[26].

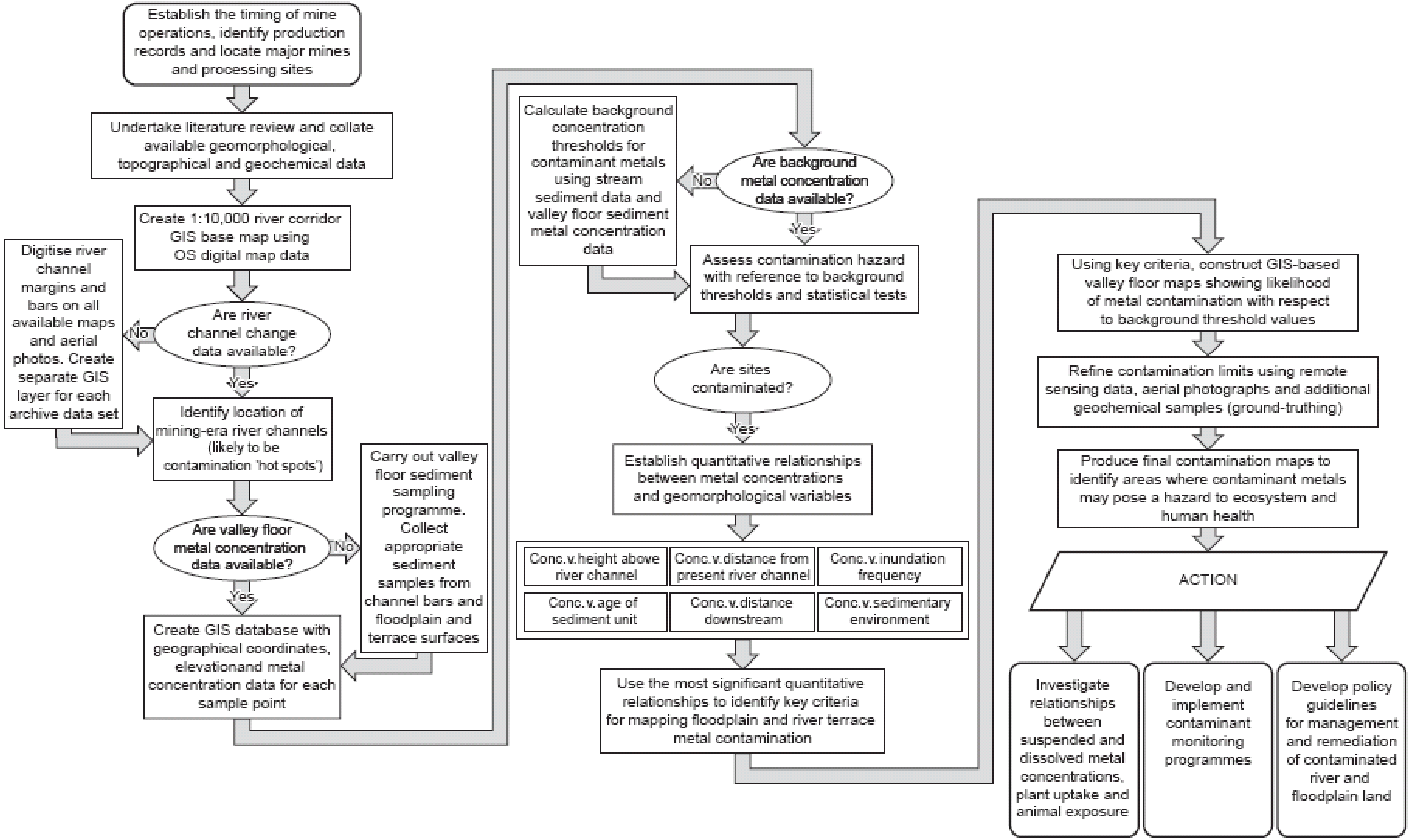


Figure 4: Geomorphologically based assessment and management scheme for historically contaminated river systems in England and Wales (this research was originally funded by DEFRA and the Environment Agency)[27].

The key elements in this management scheme are:

- Identifying the location of major mines, processing sites and the watercourses they polluted.
- Establishing when and for how long metal mining and processing took place.
- Using large-scale O.S. maps to delineate the position of river channels downstream of mines, that were active during the period of metal ore extraction and processing, and therefore usually still contain high levels of metal pollutants.
- Identifying floodplain surfaces inundated by flood flows during the mining era, which are likely to have high heavy metal concentrations. All of these data can be readily entered into a Geographic Information System (GIS) to produce contaminant hazard maps (see Figure 5). Using a classification endorsed by the Department for Environment, Food and Rural Affairs (DEFRA) these contaminant hazard maps enable three hazard zones to be identified[28]:

1. Areas with a high probability of land contamination - river channel and floodplain sediments deposited during/since the period of mining and metal processing.
2. Areas with a likelihood of contamination - floodplain surfaces inundated while mines and ore processing plants were in operation and since their closure.
3. Areas with a low probability of metal contamination - valley floor areas unaffected by flooding during/since the mining era.

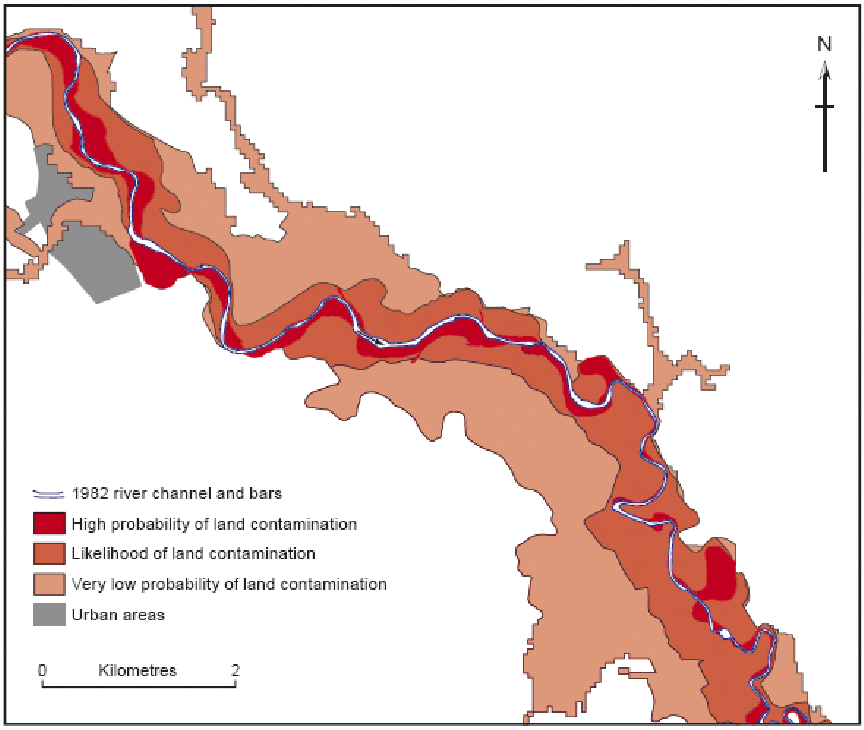


Figure 5: Example of floodplain hazard maps from the River Swale, southeast of Catterick, North Yorkshire showing probability of contamination[29].

The management process developed by Macklin and his colleagues, includes a GIS-decision making tool for evaluating environmental health standards associated with sediment and heavy metal soil contamination. It produces information with a spatial resolution of ± 100 m. This can then be used in conjunction with lower resolution (± 10 km) maps recently produced for England and Wales that show catchments potentially at risk from sediment-borne contamination caused by past metal mining[30] (See Figure 5). There is an urgent need for information of this kind, particularly at a floodplain scale, from local authorities and environmental agencies, and from the UK Food Standards Agency, who are responsible for evaluating some of the health risks arising from flooding. These organisations currently have no systematic information about historical pollution sources which become re-activated either by increased erosion of contaminated floodplains or through changing land-use which unintentionally brings contaminated land back in to food production.

7 EXTENDING THE FLOOD RECORD AND DETECTING CHANGE IN THE FLOOD SERIES

Projecting future changes in our climate requires more definite information on the magnitude and frequency of major floods over time than short instrumental records currently provide. Without accurate records, insurers and policymakers can struggle to identify vulnerable areas. Gauged river flow records in the UK are remarkably short, an average of around 45 years and many catchments in upland and sparsely populated areas are un-gauged. This makes it difficult to accurately estimate the frequency of large floods with 1% or less annual exceedance probabilities, particularly at a time of a rapidly changing climate. Indeed, the longest gauged records[vii] in the UK of fluvial-flood and high-flow trends offer no clear evidence for changes in either flood frequency or magnitude above that of natural variability over the last few decades[31]. Given the relative brevity of the flood record, realistically predicting recent widespread UK floods, such as those of Spring 1998, Autumn 2000, Winter 2003 and Summer 2007 has been extremely difficult. Relating these events to climate change has proved even more problematic[32]. Currently, recent modelling has suggested a link between flooding and climate change. However, although there are physical reasons why continued warming would increase the intensity and frequency of flooding, the observational and historical records currently do not show evidence of this.

Therefore, one of the primary challenges for river scientists in the UK and internationally is to find new methods for extending the flood series to establish if floods are becoming more frequent and/or larger, as well as determining if this relates to recent climatic fluctuations and/or anthropogenic land-use and land-cover changes. This has been a rapidly developing field of research over the last decade and two principal ways of extending flood records have emerged; the use of documentary sources, and the sedimentary archives of floodplains.

7.1 DOCUMENTARY SOURCES

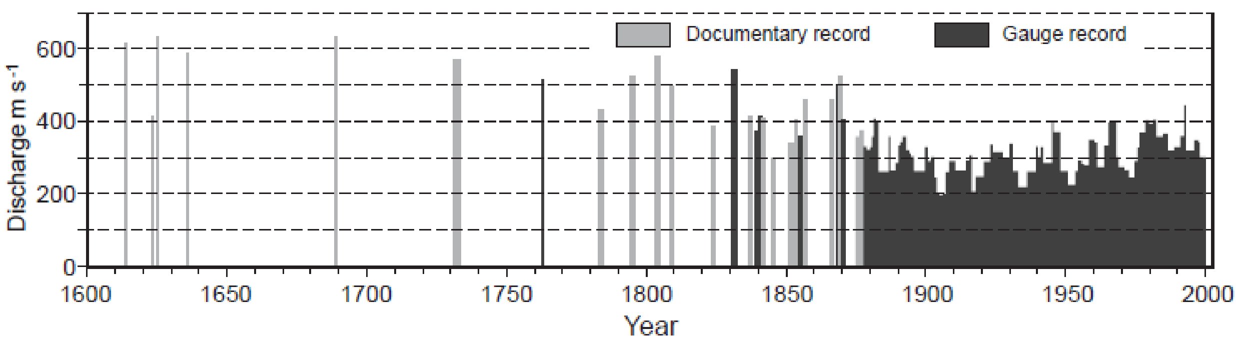


Figure 6: Documentary and gauged annual maximum flow records at York[33].

Historical flood records appear in many locations and formats in the UK. The British Hydrological Society's *Chronology of British Hydrological Events* website[34] provides an effective and efficient means of quickly identifying hydrological information. One of the best examples of using historical data to extend the flood series is from the river Ouse in the city of York, where epigraphic markings of flood heights above a standard level (known as a datum) are available from 1263-1875[35]. Used with gauged records beginning in 1877, these enable the evaluations of the city's long-term flood risk (see Figure 6).

This shows that although there were five events between 1263 and 1875 that exceeded the Autumn 2000 flood, the flood peak in central York on 4 November 2000 was the highest in the 123 year period between 1877 and 2000. By extending the flood series to incorporate records of historical floods into the flood risk analysis, the return frequency estimates for the November 2000 flood increases from 38 years, based on the relatively short gauged record, to a return estimate of 102 years[36].

[vii] The longest river flow records in the UK go back to the late 19th century with the gauge record at York starting in 1877

As a result of short-term climatic fluctuations (controlled primarily by the North Atlantic Oscillation NAO) and changes in catchment land-use, the longer-term flood risk estimates are showing no change. This was evaluated in a 1999 study that demonstrated a discontinuity in the flood series in the mid-1940s. This was characterised by an increase in flood frequency linked to the drive to convert land to agricultural use in order to meet the demand for increased home food production during World War Two[37].

NORTH ATLANTIC OSCILLATION

Since 1969, there has been an increased frequency of larger floods in the river Ouse catchment generated by cyclonic (low pressure systems that bring wet and windy weather to the UK) and south-westerly weather types. This supports a growing body of geomorphological and hydro-climatological research showing that changes in the frequency and magnitude of floods over decadal and multi-decadal time periods in the UK can be linked to large-scale shifts in atmospheric circulation and jet stream over the North Atlantic region governed by the North Atlantic Oscillation (NAO)[38]. Although changes in the NAO have been shown to cause increased flooding, the link between climate change and the NAO is at present unclear.

The NAO index NAOI (the difference of atmospheric pressure at sea-level between the Icelandic low and the Azores high) influences the dominant storm track over the North Atlantic into Europe. This is particularly evident during the winter period. In positive NAOI years, stronger westerly airflows and more northerly storm tracks cause increased winter precipitation and flooding over northern and western parts of the UK. In contrast, when the NAOI is negative, westerly airflows are suppressed, precipitation is generally lower, and the UK suffers cold winters. The exceptionally cold Winters of 2009-10 and 2010-11 in the UK coincided with extremely negative NAOI and a ‘blocking high’ over Greenland that forced cold Arctic air south towards the UK.

The NAO influences UK weather most strongly in winter but can also affect rainfall and flooding in summer. During a positive NAO phase, westerly winds keep the UK cool and damp, while under negative NAO phases, blocking conditions produce hot, dry summers and an increased risk of flash flooding from convective storms. The extreme upland flooding over the last 200-300 years appears to be associated with negative NAO values[39]. Indeed, many of the largest historical floods in the major catchments of the UK also occurred during periods characterised by negative NAO, the majority of which were generated by rain-on-snow events[40].

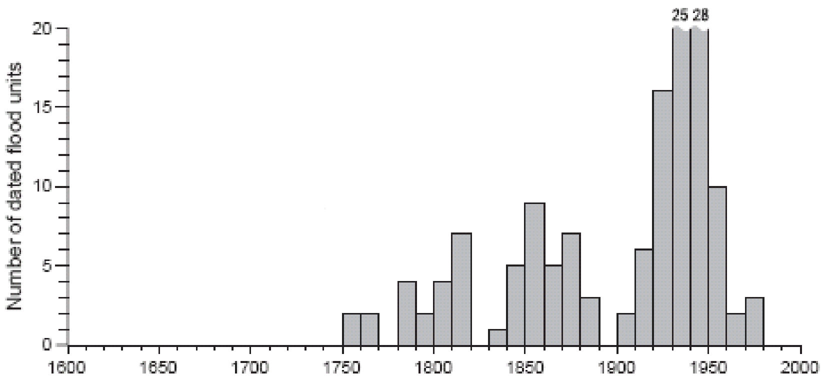
The NAO showed a downward trend from the 1930s to the 1960s, becoming generally negative. The index increased from 1960 to the early 1990s, but has declined since then with the 2009-10 Winter having the most negative NAO index during the 190-years on record[41]. In the period 1961-2000, daily precipitation in the UK changed, becoming on average more intense in winter and less intense in summer[42]. Since 2000, this trend has reversed with fewer heavy rainfall events in winter and higher seasonal rainfall totals with a relatively high frequency of heavy daily rainfall events in summer[43]. Recent summer flash floods following heavy rainfall have occurred in Boscastle, Cornwall (2004), Ryedale, North Yorkshire (2005) and Alston, Cumbria (2007).

7.2 SEDIMENTARY ARCHIVES

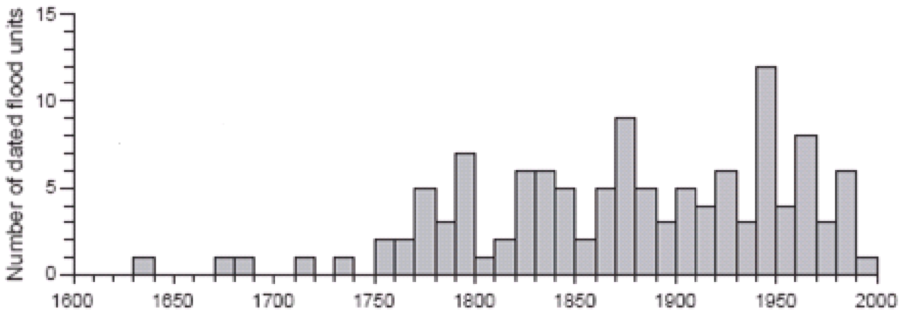
Finding climate-related signals in the UK’s relatively short gauged flood record, as well as quantifying the impacts of land-use change on the hydrology of large catchments has proved complex. To overcome this, geomorphologists have increasingly turned to geological archives of floodplains that contain evidence of past floods in the form of distinctive sedimentary deposits.

In the upland catchments of northern and western UK these deposits are found in the build-up of boulders and large cobbles (termed ‘Boulder Berms’) that were transported by the same type of very large and powerful flows of water that affected Boscastle in 2004. These can be dated using lichenometry, which is based on the assumption that when a boulder comes to rest after a flood, lichens are able to colonise newly exposed rock surfaces within a few years. Their growth rates can then be used to calculate a minimum age for the flood event lichen growth rates over the last 200-400 years have been measured on rock surfaces of a known age, such as gravestones and built structures. This method has created records of other extreme flood events, similar to the Boscastle flood, for the Northern Pennines, Lake District, Yorkshire Dales and the Brecon Beacons uplands going back to 1750 and even to the 17th century in some areas[44]. These are amongst the longest upland flood records in Europe and show that both the incidence and size of extreme events have significantly decreased in the last 50 years. In some catchments they may be at their lowest level since the late nineteenth century or earlier (see Figure 7). This indicates that the widely held perception by the general public (often as a result of short term institutional memory) - that the incidence of extreme flood events in upland areas is increasing, is not currently supported by longer-term (multi-centennial) sedimentary flood records, that show an increase in flooding incidents throughout the 17th and 18th centuries, followed by a general decline in reported flooding incidents in the late 20th century[viii] . However, a decline in the frequency of flood events does not necessarily mean that there will not be a signficiant increase again in the future. Indeed, physical processes in the atmosphere will ensure that there will be increases in rainfall magnitude, frequency and/or timing with continued climate change. Common practice within the insurance industry is to price risks based on the recent past. This may result in the inappropriate pricing of risks in the future, as the past claims experience may not accurately reflect future trends in flooding.

NORTHERN PENNINES, ENGLAND



YORKSHIRE DALES, ENGLAND



ENGLAND AND WALES, ALL REGIONS

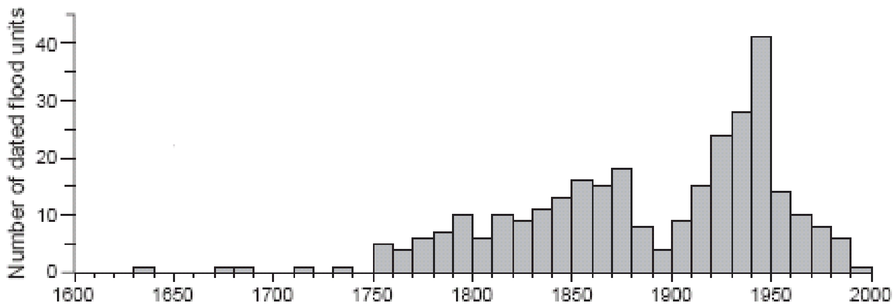


Figure 7: Incidence of extreme upland flooding in selected regions of England and Wales over the last 200-300 years[45].

[viii] It is not clear what was the cause of the rise in flooding events during the 17th and 18th centuries. This may have been in response to changes in Little Ice Age climate and/or shifts in the NAO.

Although geomorphological-based flood records were first developed and tested in the early 1990s[46] this approach has not been used by flood risk assessment and management agencies in the UK. With the scarcity of gauged flows in UK upland catchments, analysis of sedimentary flood records is usually the only way to accurately estimate the magnitude and frequency of events and their associated flood risk. Furthermore, evidence from extended flood series, and the fact that most of the UK's major water storage and supply dams were built in the Victorian era and are found in upland catchments, suggests an urgent need to evaluate dam safety and the risk of their overtopping.

Long-term sediment-based flood records are also being compiled in lowland floodplains[47]. In the upper Severn catchment a continuous record of overbank flooding has been reconstructed for the last 3,700 years, which shows abrupt changes in flood frequency over a matter of decades and corresponds to relatively wet and dry phases and variations in the NAO (see Figure 8). Extended periods of drier climate are reflected in an increased mean age of ancient oak trees preserved in Irish peat bogs, and is also characterised by a marked decrease in the occurrence of large floods[ix]. A similar pattern emerges when the floodplain sedimentary archive is compared to long-term proxy NAO records. This shows a marked reduction in large floods during the Medieval Climatic Anomaly, a time of warmer temperatures and more positive NAO, compared with periods before 1000, and particularly after 1550 during the cooler Little Ice Age (see Figure 8). These studies demonstrate repeated and significant changes in flooding patterns in the last 500-1000 years, which were very much greater than those seen in recent instrumental flow records[48]. This should concern those using flood risk estimates based only on the analysis and extrapolation of relatively short gauged flood series of 50 years or less. Finally, recent investigations of both documentary sources and floodplain sedimentary archives show that recent damaging flood events are not unprecedented, and have been more frequent in the recent past. More worryingly, there is evidence that significantly larger flood events in the last 1000 years could be repeated in the future if anthropogenic climate change continues.

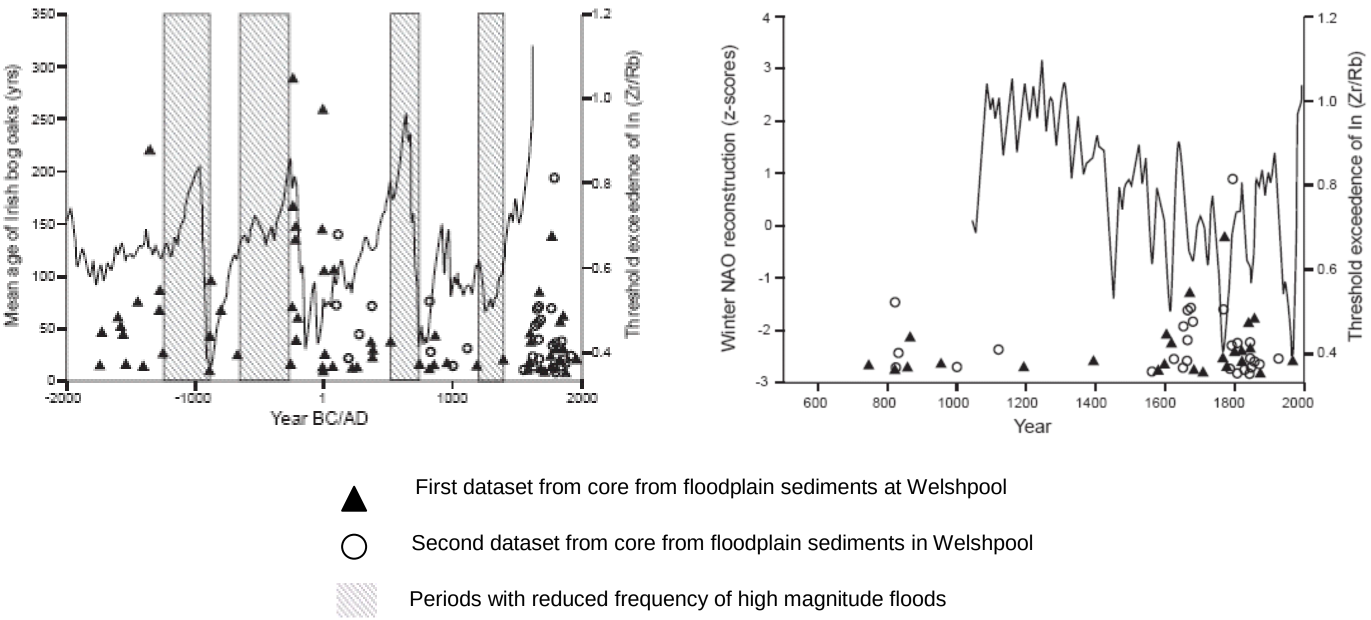


Figure 8a (left): 3700 year record of overbank flooding in the Upper Severn, Wales. Events plotted >3% of present annual exceedance probability flood.
Figure 8b (right): Comparison of Upper Severn River floods since AD 550 with NAO proxy[49].

[ix] For comparision, a large flood in this context can be compared to similar floods experienced in the present day which have a return frequency of 30 years or longer.

8 CONCLUSION

Recent research proposes that climate warming is likely to have intensified the water cycle as humidity increases exponentially with temperature[50], suggesting that current global patterns of precipitation intensity, frequency and duration will increase[51]. Satellite observations and model simulations show a strong link between rainfall extremes and temperature, with heavy rain events increasing during warm periods and decreasing during cold periods (see Lloyd's Emerging Risk report "East London Extreme Rainfall" for a analysis of rainfall trends in one region[52]).

Flooding remains the UK's most significant natural hazard and, because climate change adds uncertainty to the risk, new thinking is required for long term flood risk management. This report sets out an approach to flood risk assessment based on an understanding of past and present river channel and floodplain dynamics. It identifies vulnerability points within river networks where infrastructure, properties, and people are most at risk from damaging flooding. It also adopts a practical and easy to implement approach using O.S. map and Google Earth based aerial photographic sources that are free to use and available for the whole of the UK.

An emerging area of risk associated with increased flooding in the UK is the reactivation of sediment containing heavy metals from floodplains contaminated by historical metal mining and metal processing. These contaminants pose a significant threat to both ecosystems and human health in large areas adjacent to rivers. A geomorphological-based assessment and management scheme is needed to produce high resolution floodplain hazard maps for environmental regulators and local authorities.

Recent research demonstrates that extending flood records by using sedimentary archives of floodplains shows much greater changes in flooding patterns in the past 500-1000 years (related to fluctuations in climate) than those observed in the shorter instrumental records (c. 50 years). The damaging floods of the last decade are not unprecedented and larger flood events are evident in the recent geological record of UK floodplains.

Effective UK flood risk management requires a focus on surveyed and archived river changes, the use of historical evidence and the study of floodplain sediments. This will provide an assessment of national flood risk and help develop the necesssary risk management responses that are not only effective in the long-term, but that also environmentally realistic and robust.

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