National Hydrological Monitoring Programme

The summer 2007 floods in England & Wales – a hydrological appraisal

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Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

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INTRODUCTION

Record late-spring and early-summer rainfall across much of southern Britain in 2007 produced hydrological conditions with no close modern parallel for the June-August period. Localised flash flooding was very common and floodplain inundations were extensive and protracted from mid-June to the end of July. In the worst affected areas flooding was more extreme than the benchmark event of March 1947. This report provides a hydrological appraisal of the 2007 floods, places them in a historical context and considers the evidence for any long-term increase in the magnitude of major fluvial floods.

The 2007 floods in summary

A distinguishing characteristic of the late spring and summer of 2007 was the frequency and spatial extent of extreme rainfall events over a wide range of durations. Correspondingly, the previous maximum May-July rainfall total in the 241-year England and Wales series was exceeded by a wide margin; since 1879 no rainfall total in this timeframe has been within 100mm of that for 2007.

The record rainfall produced hydrological conditions with no close modern parallel for the summer period. Localised flash flooding was very common and floodplain inundations were extensive and protracted from mid-June to the end of July. In the worst affected areas flooding was more extreme than in March 1947, when England and Wales suffered its most extensive flooding of the 20th century.

Three storms in June and July were of particular significance, the latter two being the immediate cause of the most devastating of the summer floods. Exceptional rainfall from 13th-15th June, in a band extending across the Midlands to the North East, generated significant flooding and left many catchments very vulnerable to further rainfall. In the final week of the month, a second slow-moving, low-pressure system produced outstanding rainfall totals from Worcestershire to the North York Moors; many local and catchment rainfall records were eclipsed.

In southern Britain, the most exceptional rainfall was associated with a storm on the 19th-20th July. A moist, subtropical airmass moving north from France became very slow moving over central England, resulting in extreme rainfall totals over a range of durations. Storm totals were most exceptional across the Cotswolds and the lower part of the Warwickshire Avon basin. At Pershore College (Hereford and Worcestershire) rainfall exceeded 10mm for six successive hours from midday on the 20th, and the 16-hour total (to 22.00 hrs) reached 134.8mm. A storm of this magnitude has a probability of occurrence of around 0.1% in any one year.

Following a dry early spring in 2007, notably dry soil conditions exerted a moderating influence on flood risk during May but, thereafter, soils wetted up rapidly. By late July, soils across much of England and Wales were at their wettest for the time of year for at least 50 years. As a consequence, catchments were as responsive to rainfall during much of June and July as is normally the case in winter.

In a global context, UK rivers are mere streams and flooding is rarely of a magnitude to constitute a substantial threat to lives and livelihoods. This is especially true of the summer, when flooding is extremely unusual at a regional rather than a catchment or local scale. However, with near-saturated soils and rainfall of the magnitude experienced in the summer of 2007, extensive flooding was inevitable. The seasonal focus, the extent of the floodplain inundations and the frequency of flash flooding sets 2007 apart in relation to major UK flood events in the modern era.

Widespread and severe flooding afflicted many river basins in June and July 2007. In some areas – parts of the lower Severn basin, headwater tributaries of the Thames, and Yorkshire and Humberside, in particular – peak river flows exceeded previous recorded maxima by wide margins. In many river reaches, the design limit of flood alleviation schemes was exceeded; similarly the design capacities of urban drainage systems were exceeded in many areas. An unusual, and very significant, feature of the summer flooding was the high proportion of damage not attributable to fluvial flooding. Around two-thirds of the properties affected (>8,000 in Hull alone) were inundated as drains and sewers were overwhelmed following the summer storms.

Some localities were subjected to a sequence of separate flood episodes and, in the lower reaches of many major river basins (e.g. the Don, Aire and the Severn), floodplain inundations were very protracted. The sustained high flows had a particularly severe impact in some urban areas (e.g. Doncaster, Sheffield and Tewkesbury), where continuing high water levels in major rivers provided only limited potential for the floodwaters to drain away from stricken communities.

Sustained high summer flows in groundwater-fed streams and rivers are especially rare. In 2007, however, a combination of record summer groundwater contributions and significant surface runoff saw outstanding flow rates in many spring-fed rivers. New maximum flows were established from the North York Moors to the Berkshire Downs, with remarkable flows characterising many Chalk streams.

Outstanding summer groundwater levels in some Chalk and limestone aquifers implied that, even with average rainfall through the autumn and winter, there would be a significant risk of groundwater flooding in vulnerable parts of the Chalk outcrop. Fortunately, England and Wales experienced its second driest August-October period since 1978, allowing groundwater level recessions to be re-established, and substantially reducing, but not eliminating, the risk of groundwater flooding through the winter of 2007-2008.

For most of those directly affected, the scale of the flooding was beyond anything experienced in their lifetime. Fourteen fatalities were linked to the flooding* and many thousands of people suffered prolonged misery as a result of floodwater inundation – sometimes repeatedly – of their properties. Over 55,000 homes and 6,000 businesses were flooded and related insurance claims were approaching £3 billion by the end of 2007. Many flooded and low-lying localities had to be evacuated and an assessment by the emergency services suggests that the summer of 2007 saw the greatest number of search-and-rescue missions in this country since the Second World War.

A number of major flood episodes in the early years of the 21st century has fuelled speculation that flood risk is increasing due to global warming. By their nature, however, any cluster of extreme hydrological events cannot readily be linked directly to climate change. The 2007 flooding was remarkable in its extent and severity, and truly outstanding for a summer event. It underlined the UK's continuing vulnerability to climatic extremes but long-term rainfall and river flow records confirm the exceptional rarity of the hydrological conditions experienced in 2007. A synthesis of the rainfall and river flow evidence indicates that the summer was a very singular episode. The associated fluvial flooding does not constitute an element in any established hydrological trend or appear to form part of a pattern consistent with currently favoured climate change scenarios.

* *The Pitt Review* [33]

Before the floods

The winter of 2006-2007 was the equal fourth warmest in the Central England Temperature series,[1] [2] which begins in 1659. It was also notably wet across much of southern Britain. England and Wales registered the third wettest October-February period since 1960-1961[†] but the rainfall was relatively evenly distributed through time and notable flood events were rare. Overall aquifer recharge was substantially greater than for the preceding two winters and, after protracted and severe drought conditions in 2006,[3] groundwater levels had generally recovered to within their normal range by early spring 2007.

An exceptionally arid episode, beginning in the second week of March and continuing through the warmest April on record, resulted in steep increases in soil moisture deficits. Normally, the absorptive capacity of dry soils substantially moderates flood risk throughout the summer. In 2007, this natural buffering seemed likely to be particularly influential: early May soils were the driest on record for England and Wales as a whole.

Synoptic conditions then changed decisively. The Jet Stream, which influences the paths taken by weather systems in the North Atlantic, adopted an abnormally southerly track and the seasonal extension of the Azores high pressure cell across the UK, which brings settled weather conditions in most summers, failed to become established.[4] With Atlantic sea surface temperatures well above average, a sustained sequence of moisture-laden low pressure systems produced outstanding 10-week rainfall totals punctuated by widespread severe flooding in June and late July.

Rainfall

Overview of the Summer

The summer (June-August) of 2007 was the wettest for England and Wales since 1912[5] but the most extreme rainfall occurred within the May to July period. In this timeframe, most of southern Britain registered more than twice the 1961-1990 average rainfall (Figure 1), approaching, or exceeding, 300% of average in those areas where the flooding was most severe.

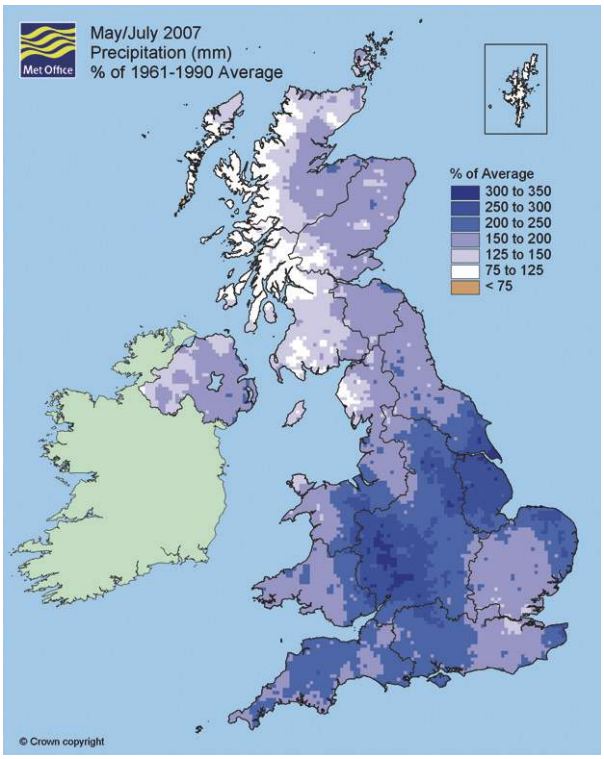


Figure 1: *May-July rainfall as a percentage of the 1961-1990 average*

[†] *Based on the Met Office (National Climate Information Centre) series from 1914*

Table 1 confirms the outstanding character of the May-July rainfall in 2007. For England and Wales, the previous maximum, in a series from 1766,[5] was exceeded by a wide margin, and since 1879 no May-July total has been within 100mm of that for 2007. Although around 15 wetter three-month periods can be identified in the England and Wales rainfall series, none since 1912 falls in the summer half-year.

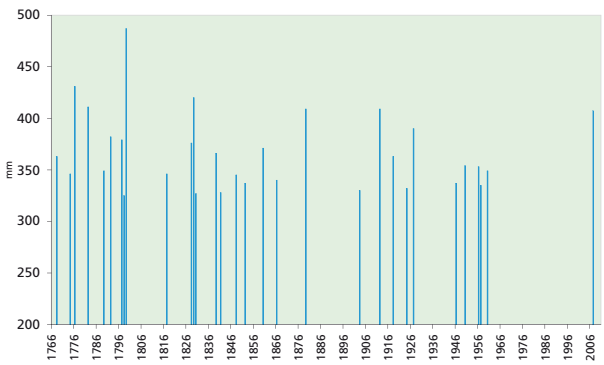
Table 1: *Highest May-July rainfall totals for England and Wales*

Rank	Year	mm	% of 1971-2000 average
1	**2007**	**415**	**223**
2	1789	349	187
3	1879	342	184
4	1828	330	177
5	1782	329	177
6	1797	324	174
7	1830	323	173
8	1766	319	171
9	1768	317	170
10	1860	315	169
11	1817	313	168
12	1777	312	167
13	1924	308	165
14	1779	307	165
15	1816	304	163

Figure 2 plots the 30 wettest (non-overlapping) three-month sequences in the April-September timeframe. The plot emphasises the singular nature of the summer of 2007 in relation to the recent past; the wet summer has no close parallel – at the national scale – in the last 50 years. Wet sequences of months in the summer half-year were rather more common prior to the 20th century, and cluster notably in the late 18th century (see Table 1 and Figure 2).

In 2007, May was the second wettest in 75 years for England and Wales, June the wettest since 1860 and July the wettest since 1888. The combined rainfall total for June and July is without recorded precedent and substantially exceeds the rainfall for any such pairing in the 20th century. Rainfall from mid-June to late July was particularly outstanding, with some areas (e.g. in South Yorkshire and Lincolnshire) registering more than 40% of the average annual rainfall in less than six weeks.

Figure 2: *Highest three-month rainfall totals in the summer (April-Sept) for England and Wales*



Flood-generating rainfall

Very localised downpours of tropical intensity are a feature of many English summers and 24-hour rainfall totals exceeding the monthly average are not especially rare, typically occurring, on average, once in 5-20 years in any one location. However, a distinguishing characteristic of summer 2007 was the frequency and spatial extent of extreme rainfall events.

In May, active frontal systems (with embedded convective cells) produced two notably wet interludes, the second (on the 27th-28th) causing localised flooding and widespread transport disruption. Torrential local downpours, over a range of durations, continued throughout June and July. Bangor (Northern Ireland) reported 20mm in 15 minutes on 12th June whilst both Manston (Kent) and Maidenhead (Berkshire) registered around 50mm in an hour on the 19th.[6] Intense short-duration rainfall events triggered locally severe flash flooding throughout much of the summer – particularly in urban areas where impermeable surfaces predominate – but the most damaging hydrological impacts followed sustained heavy rainfall over periods of 10-36 hours, mostly associated with very slow-moving frontal systems. Three storms in June and July were of particular significance, the latter two being the immediate cause of the most devastating of the summer floods.

Table 2 provides details of a selection of extreme rainfall events during the three major storm episodes. Standard 12- and 24-hour durations have been used to allow comparisons between the storm events. Considerably lower probabilities (i.e. rarer) than those featured in Table 2 were associated with rainfall accumulations over different timespans in many of the flood-affected areas.

Exceptional mid-June rainfall in a band extending across the Midlands to the North East generated significant flooding and left many catchments very vulnerable to further rainfall. In the final week of June, a second slow-moving low pressure system produced outstanding rainfall totals from Worcestershire to the North York Moors. Substantial local variations in rainfall intensity, often reflecting the incidence of thunderstorms, were a feature of both June storms. The spatial variability is evident in Figures 3a and 3b, which map rainfall patterns in the Environment Agency's North-East Region.[7]

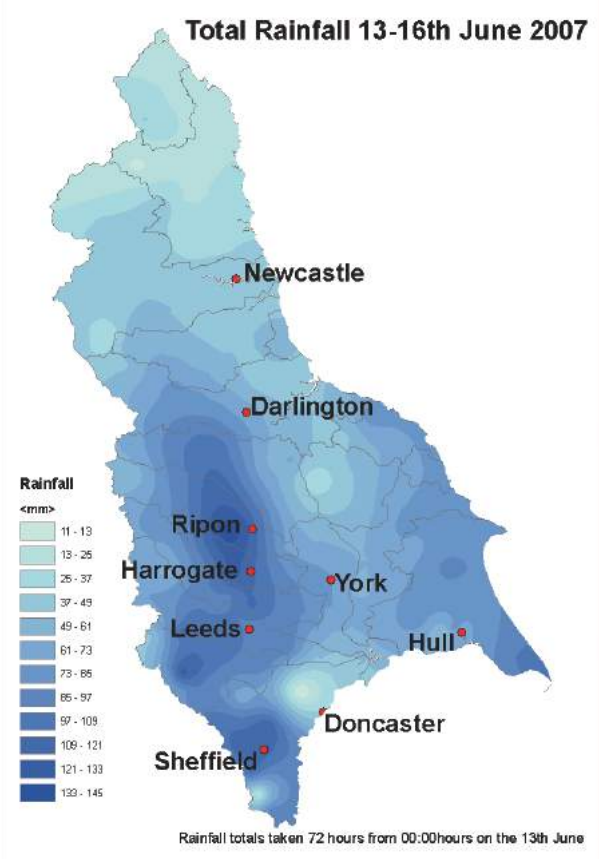


Figure 3a: *Mid-June rainfall distribution*
Source: Environment Agency

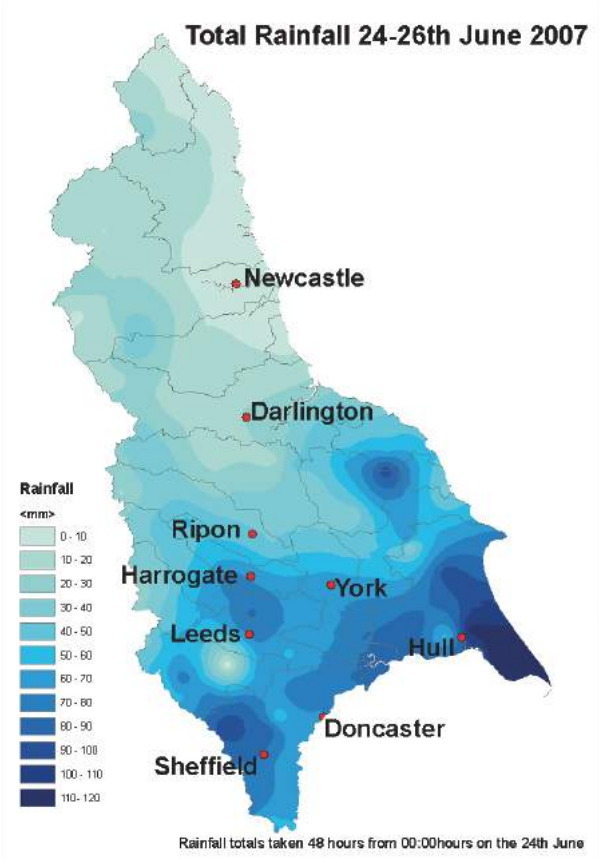


Figure 3b: *Late-June rainfall distribution*
Source: Environment Agency

On the 13th-16th, particularly extreme totals were recorded in a zone from Sheffield to Ripon. The Sheffield area was again remarkably wet on the 24th-25th, when outstanding rainfall was also registered to the east of Hull; at Winestead, a storm total of 135mm was recorded – the equivalent of over 20% of the annual average rainfall. The June storms contributed to the wettest month on record for Yorkshire (in a series from 1882)[7] and other areas, mostly in the north Midlands and Lincolnshire, also experienced intense rainfall during both June events. Table 3 lists rainfall totals over the 13 days embracing both storms; some areas registered more than 30% of their annual average rainfall in this period.

In southern Britain, the most exceptional rainfall was associated with the July storm. Late on the 19th a moist, subtropical airmass moving north from France became very slow moving over central England, resulting in extreme rainfall totals over a range of durations. Whilst a few areas remained dry (e.g. in the South West), around 30% of England and Wales recorded over 30mm of rain on the 20th and an area of around 3,500 km^2 registered >100mm, a very rare occurrence (but see page 22).

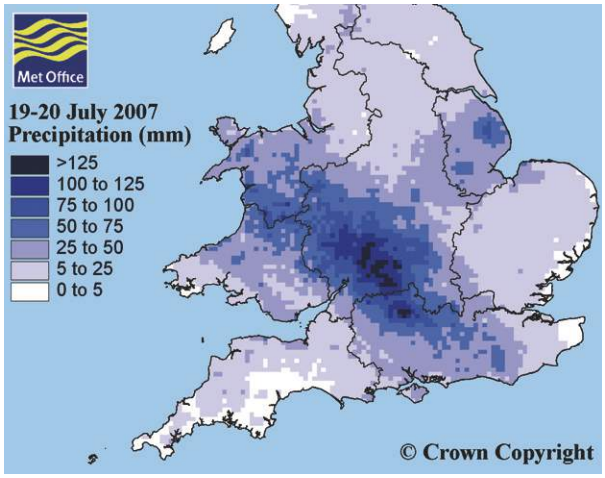


Figure 4: *Rainfall distribution 19th-20th July*
Source: Met Office

Storm totals were most exceptional across the Cotswolds and the lower part of the Warwickshire Avon basin (see Figure 4). At Pershore College (Hereford and Worcestershire) rainfall exceeded 10mm for six successive hours from midday on the 20 (Figure 5) and the 16-hour total (to 2200 hrs) reached 134.8mm – a storm of this magnitude has a probability of occurrence of around 0.1% in any one year.

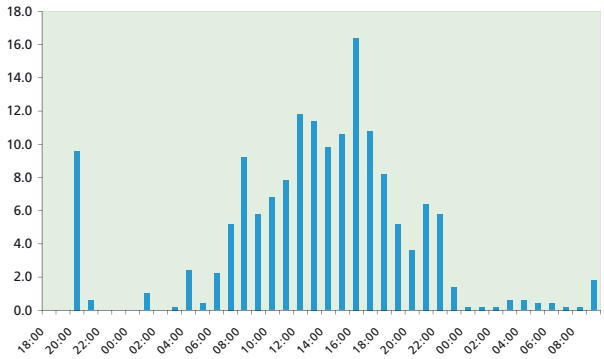


Figure 5: *Hourly rainfall for Pershore College (19th-21st July)*
Data source: Environment Agency

Table 2: *Selected rainfall events in the main flood-affected areas*

Rainguage National Grid Reference	Site Name	Catchment	County/Area	12hr Rainfall (mm)	Prob. of Occ. (%)*	24hr Rain (mm)	Prob. of Occ. (%)*
14th-15th June							
TA 300234	Winestead Booster	Hull	Humberside	69	1.8	75.2	1.9
SK 371983	Harley	Don	South Yorkshire	58.8	3.8	79.8	3.2
SE 225 706	Lumley Moor	Skell	North Yorkshire	70.8	2.9	96.2	1.8
TA 169 098	Keelby	Waithe Beck	Humberside	48.8	10.0	58.4	9.6
SP 147788	Tudor Grange	Cole	West Midlands	65	2.0	81	1.8
24th-25th June							
TA 300234	Winestead Booster	Hull	Humberside	100.4	0.4	119.8	0.2
SK 371983	Harley	Don	South Yorkshire	71.8	1.6	85	2.4
SE 347204	Wakefield	Calder	West Yorkshire	51.8	3.7	62.8	4.3
TA 169 098	Keelby	Waithe Beck	Lincolnshire	58	5.0	73	3.6
TF 321 865	Raithby	Lud	Lincolnshire	49.4	10.0	62	7.8
SK 711893	Wiseton	Idle	Nottinghamshire	58.4	4.8	74.6	3.7
SO 631 713	Bickley	Teme	Shropshire	40.8	6.0	52.8	4.5
19th-20th July							
TF 321 865	Raithby	Lud	Lincolnshire	66.4	3.2	77.2	3.1
SP 601 361	Brackley	Great Ouse	Northamptonshire	65.8	2.2	70.6	3.4
SO 631 713	Bickley	Teme	Shropshire	53.6	2.1	70.2	1.4
SP 181529	Stratford	Avon	Warwickshire	69.2	1.7	81.4	1.8
SO 960 447	Pershore	Avon	Worcestershire	113.8	0.2	142.6	0.1
SP 163392	Chipping Camden	Badsey Brook	Gloucestershire	90.2	0.9	107	0.9
SP 002280	Langley	Isbourne	Gloucestershire	110	0.2	130.6	0.2
SP 112071	Bibury	Coln	Gloucestershire	108.2	0.3	124.2	0.3
SP 294268	Chipping Norton	Evenlode	Oxfordshire	101.4	0.5	116.8	0.5
SU 343929	Stanford	Ock	Oxfordshire	88	0.7	96	0.8
SU 468739	Chieveley	Lambourn	Berkshire	89	0.8	93.2	1.2

* The percentage probability of occurrence in any one year.

As with the June storms, spatial variability was an important influence on local flood severity during the July event. Figure 6, based on a denser raingauge network than that used in Figure 4, shows the rainfall pattern for 19th-20th July across the upper Thames basin. Relatively moderate rainfall in the Chilterns contrasts with extreme totals along the Cotswolds ridge, and in a zone extending south-south-east towards Newbury,[7] where storm totals exceeded 100mm in less than 24 hours (Table 2) in a number of localities.

The range of durations and geographical spread of the exceptional rainfall totals in the summer of 2007 is remarkable. With storms of this magnitude, extensive flooding was inevitable.

Figure 6: *Rainfall distribution in the upper Thames basin, 19th-20th July*
Source: Environment Agency

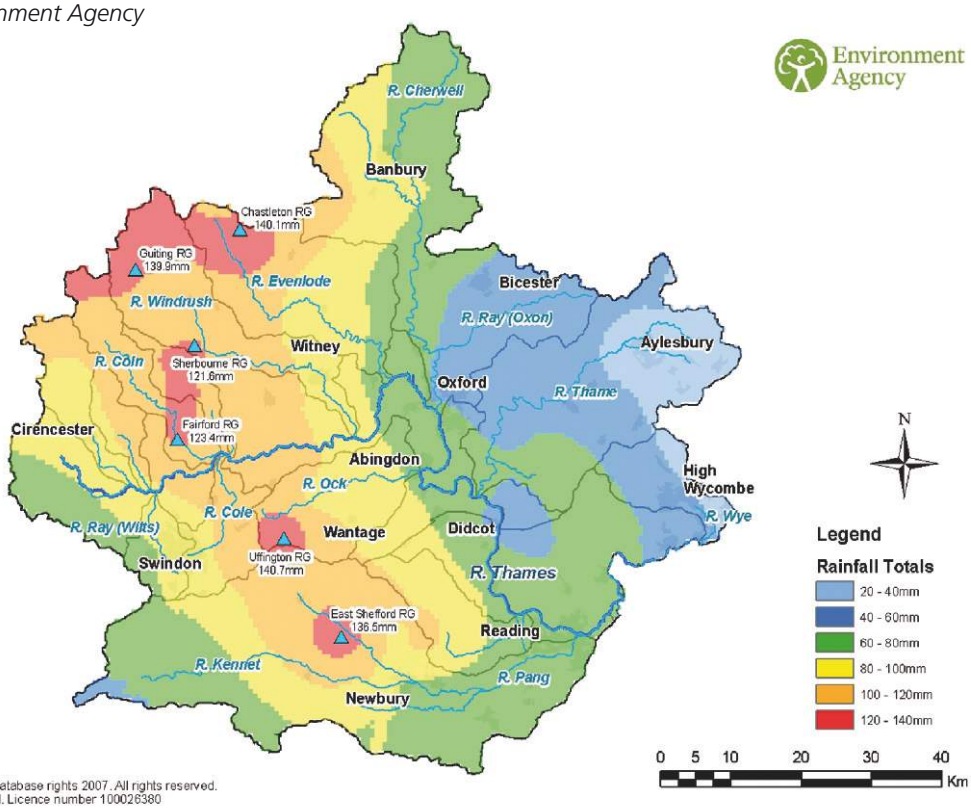


Table 3: *Notable rainfall totals: 13th-25th June*

Raingauge National Grid Reference	Site Name	Catchment	Rainfall (mm)	Average Annual Rainfall (mm)	% of Average Annual Rainfall
TA 300234	Winestead Booster	Hull	265.8	600	44
SK 371983	Harley	Don	265.6	691	38
SE 347204	Wakefield	Calder	204.2	635	32
TA 169 098	Keelby	Waithe Beck	207.2	640	32
SK 711893	Wiseton	Idle	203.8	595	34
SP 147788	Tudor Grange	Cole	160	715	22

Soil moisture conditions in 2007

Generally, wet soil conditions are a necessary pre-requisite for extensive and protracted fluvial flooding. Correspondingly, over 70% of UK floods occur during the October-April period. This is not primarily a consequence of seasonal contrasts in rainfall amounts: winter half-year rainfall is on average not substantially greater than for the summer half-year. In a normal summer however, increasing temperatures and accelerating evaporative demands lead to a progressive drying of the soil profile, creating what is termed a Soil Moisture Deficit (smd). Ordinarily, this deficit increases until the late summer and the dry soils are able to absorb the greater part of the summer rainfall, thus greatly moderating flood risk.

In 2007, the development and decay of soil moisture deficits was extraordinary, with very wide departures from the normal seasonal pattern. Figure 7 shows modelled daily smds for the Berkshire Downs for 2007 together with the long-term daily average and extreme values. During March and, particularly, April soils dried rapidly but, thereafter, soil moisture levels recovered very briskly. For significant periods in June and July, soils were wetter than is normally the case in the early winter. Conversely, in September, when smds normally decline, soils dried considerably – returning to typical autumn values in October in most areas. Broadly, this pattern was repeated across much of southern Britain; many catchments were close to saturation for a considerable proportion of the summer.

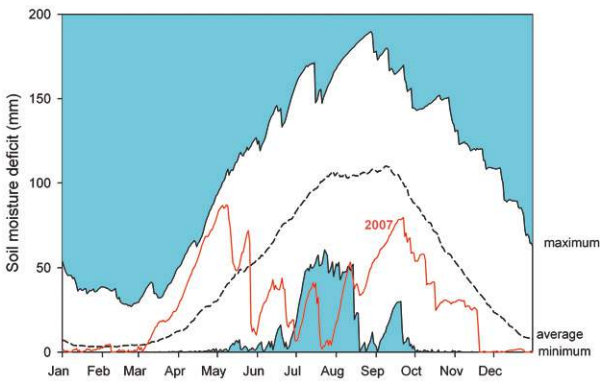


Figure 7: *Soil moisture deficits (in mm) for the Berkshire Downs*

Considering England and Wales as a whole, end-of-April soils in 2007 were the driest on record in a series from 1961. In a remarkable transformation, by the end of July smds were very modest across much of the UK (see Figure 8); 80mm or more below average over large parts of the English Lowlands.[9] Soil moisture conditions were spatially very variable in many areas but the seasonally outstanding soil wetness during mid-summer is emphasised by Figure 9 which compares end-of-July smds (for England and Wales) for each year in the MORECS[8] series. In 2007, soils in late July were wetter than the late-winter average, and the wettest on record for the time of year by an appreciable margin.

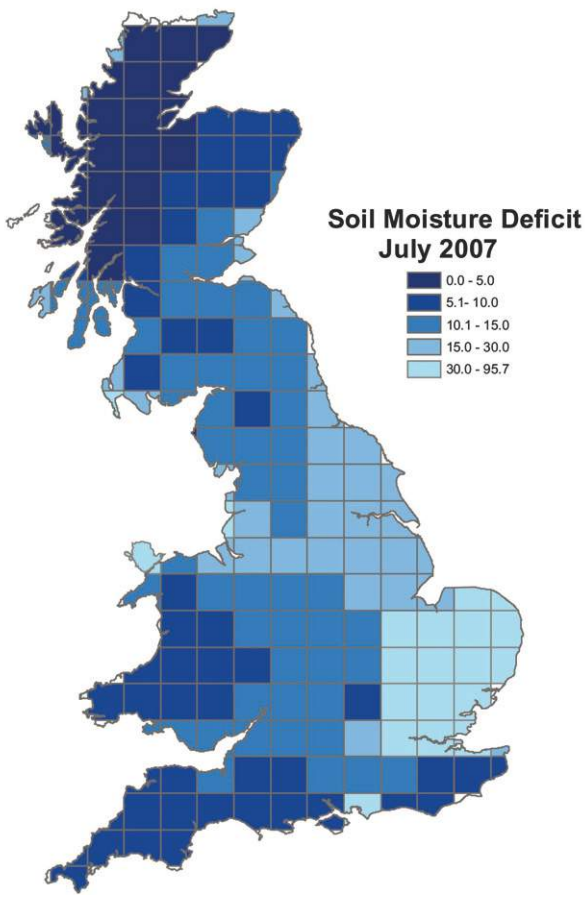
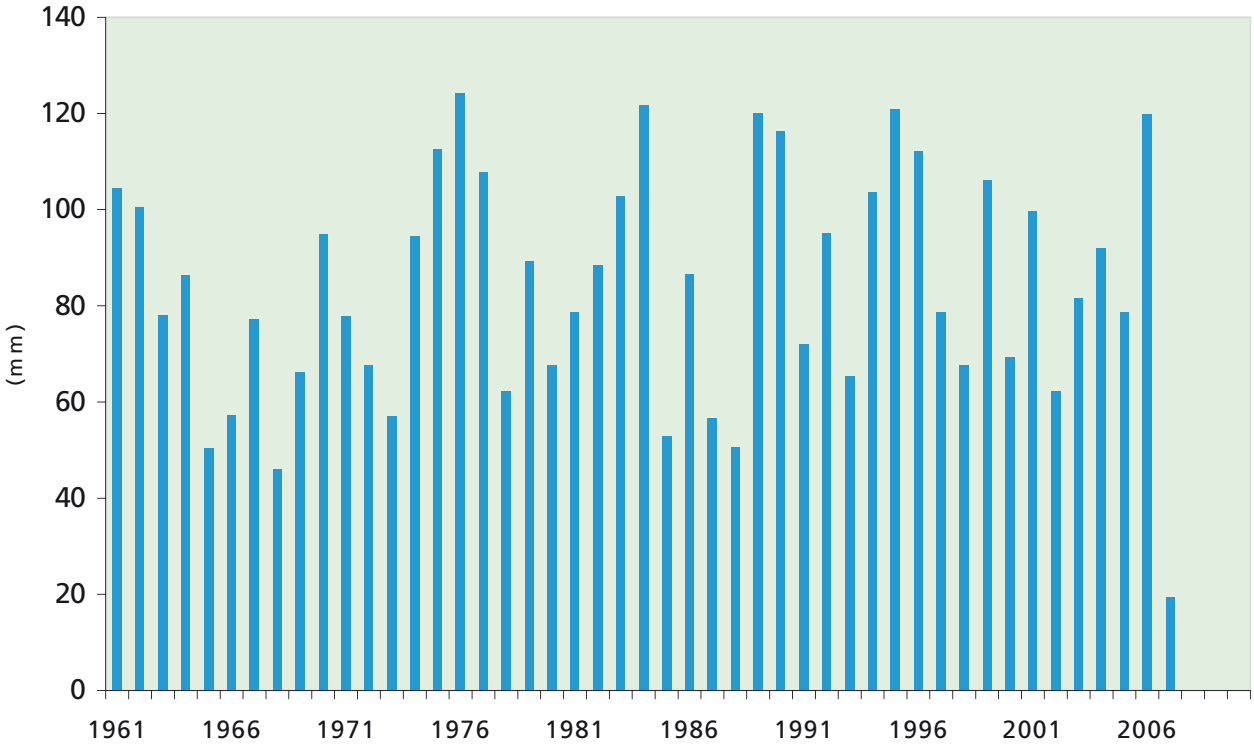


Figure 8: *Soil moisture deficits (for a grass cover) at the end of July 2007. Source: MORECS[8]*

Figure 9: *End-of-July soil moisture deficits for England and Wales*



River flows

Overview of the 2007 floods

In a global context, UK rivers are mere streams and flooding is rarely of a magnitude to constitute a substantial threat to lives and livelihoods. This is particularly true of the May-September period but severe summer flooding does occur, as happened at Boscastle in 2004, and can be devastating in its effect. The Lynmouth flood of August 1952 was responsible for 34 fatalities.[10] It is very unusual, however, for summer flooding to impact at a regional rather than a catchment scale. The seasonal focus, the extent of the floodplain inundations and the frequency of flash flooding (also known as pluvial flooding) sets the summer of 2007 apart in relation to major flood events in the modern era (see page 22).

The vulnerability of England and Wales to extreme rainfall was heavily underlined when widespread and severe flooding afflicted many rivers basins in June and July 2007. In some areas – parts of the lower Severn basin, headwater tributaries of the Thames, and Yorkshire and Humberside in particular – the flooding was more severe than in March 1947, the most extensive flood episode in England and Wales during the 20th century (see page 23). Whilst river flows in the worst-affected areas were extreme, an unusual, and significant, feature of the summer flooding was the high proportion of damage not immediately attributable to fluvial flooding. Around two-thirds of the properties affected (>8,000 in Hull alone) [7] were inundated as drains and sewers were overwhelmed following the summer storms.

Some localities were subjected to three or more separate flood episodes and in the lower reaches of some major river basins (e.g. the Don, Aire and the Severn) floodplain inundations were very protracted. The sustained high flows had a particularly severe impact in some urban areas (e.g. Doncaster, Sheffield and Tewkesbury), where continuing high water levels in the major rivers provided only limited potential for the floodwaters to drain away from the stricken communities; in Hull, tide levels had a similar effect.

Timetable of the flooding

Seasonal river flow recessions in 2007 were well established by early May[6] but a foretaste of the summer conditions was provided by localised urban and rural flooding in many parts of the country during the final week of the month. On the 27th-28th, 24-hour rainfall totals of greater than the monthly average occurred

at many locations in the English Lowlands. At Runley Wood (Luton) a 79.2mm storm triggered severe local flooding and transport disruption.[6] As catchments wetted up across most of southern Britain, river flows generally increased steeply, heralding a seven-week period punctuated by local and more extensive flooding of exceptional magnitude.

The first widespread flooding followed sustained heavy rainfall on the 13th June. Especially high river flows were reported in a band from Northern Ireland to Lincolnshire. Previous maximum recorded flows were exceeded in a number of rivers, including the Annacloy (Northern Ireland), Cole (Warwickshire) and Waithe Beck (Lincolnshire); the latter in a 47-year record.

The most extensive floodplain inundations during the summer of 2007 were associated with the two remarkable storm events in late June and July. Although having differing spatial footprints, there were similarities between the two flood episodes. Typically, intense rainfall initially triggered localised, flash floods – even in permeable catchments – as agricultural drainage ditches and, particularly, drains and sewers in urban areas were overwhelmed (Plate 1). At a local level, many properties were exposed to flooding in areas with no recent history of inundation (Plate 2). Thereafter, extreme flows were reported in many responsive streams and small rivers (Plate 3). As the floodwaters coalesced in the major rivers (from the Yorkshire Ouse to the Upper Thames), floodplain inundations were widespread and protracted (Plate 4).

Plate 1: *Flash flooding – Abingdon, July 2007*

Plate 2: *Surface runoff – South Croxton, Leicestershire, July 2007*

Plate 3: *Red Brook – Shrewsbury, July 2007*

Plate 4: *River Severn – Tewkesbury, July 2007*

Magnitude of the floods

The magnitude of the 2007 flooding is examined below using a range of indices – from summer runoff totals at the national scale to estimates of the probability of occurrence of peak river flows in the worst affected rivers.

Runoff in June and July

A guide to the outstanding nature of runoff patterns in the late spring and early summer of 2007 is provided by Table 4, which ranks the combined June-July runoff totals for England and Wales as a whole[§]. In a national series from 1961, the June-July runoff in 2007 was well over three times the long-term average and nearly twice the previous maximum (registered in 1968). However, the normal seasonal variation in runoff patterns is such that the June-July 2007 outflows for England and Wales are unremarkable when viewed in the context of two-month maxima for any season. For example, the summer 2007 outflows were clearly exceeded by the combined outflows of December 2006 and January 2007, and less than half the runoff registered in November-December 2000. It was the concentration of the most exceptional runoff into several major basins that caused the extensive flooding in the summer of 2007.

The regional extent of the exceptional runoff in the summer of 2007 is indicated by Figure 10, which shows June-July runoff expressed as a percentage of the long-term average for a network of index catchments across the UK. The black shading indicates a probability of occurrence in any given year of <5%, and encircling arrows signify new period-of-record maxima. Record June-July runoff totals were established from the Ness catchment in northern Scotland to the Dart (Devon). In England, many rivers reported three times their average June-July runoff and almost all index catchments exceeded their previous maximum runoff, often by very large margins. At Evesham, runoff for the Warwickshire Avon was 80% greater than the previous June-July maximum in a 70-year record; only two two-month episodes (both during the winter half-year) have generated higher runoff totals since 1960. As exceptional, in a hydrological sense, was the record late-summer runoff for a number of rivers draining Chalk or limestone catchments. Abundant outflows from springs and seepages kept flows in a number of such rivers (including the Lud, Coln and Lambourn) close to, or above, previous daily maxima into the early autumn (Figure 11).

Table 4: *Estimated June-July runoff for England and Wales*

Rank	Year	mm	% of Long-term Average
1	2007	121.5	332
2	1968	61.8	169
3	1985	52.0	142
4	1998	50.4	138
5	1972	49.8	136
6	1987	49.3	135
7	1988	48.1	132
8	2000	47.2	129
9	1993	46.1	126
10	2002	42.8	117

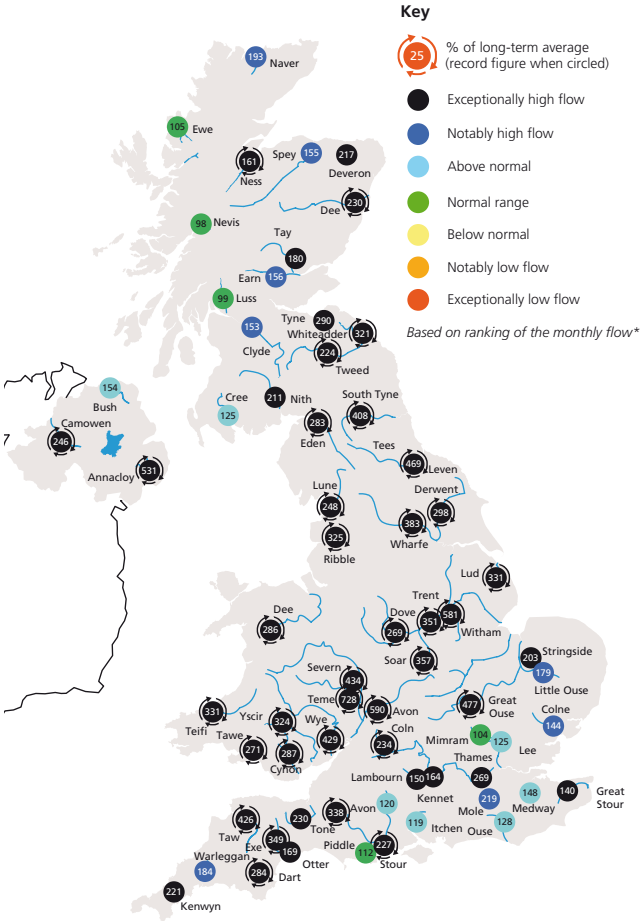


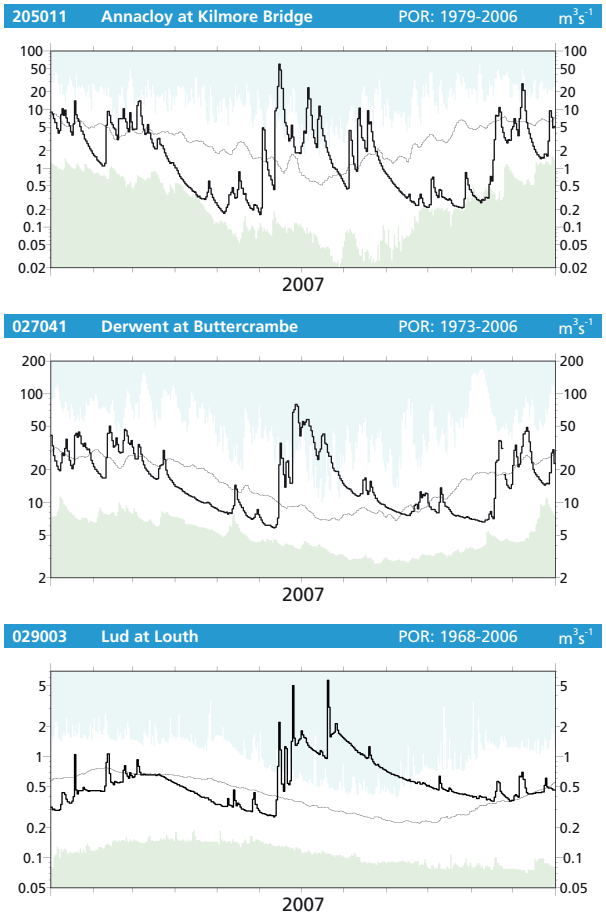
Figure 10: *June-July 2007 runoff as a percentage of the previous average*

[§] *Based on outflows from 18 major river basins.*

Flow regimes

Across a considerable proportion of England and Wales, summer high-flow regimes were largely redefined during 2007, particularly for gauging stations with relatively short records. The extension in the range of recorded summer flows is well illustrated in Figure 11, which shows daily flow hydrographs for eight index rivers. The blue envelope illustrates the highest pre-2007 flow for each day of the year; also shown are the daily minima (green envelope) and the long-term daily mean (grey trace).
The incursions of the 2007 hydrograph into the blue envelope emphasise the exceptional nature of the summer flows. Correspondingly, notable spates were very common for both responsive rivers (e.g. The Dover Beck) and those draining more permeable catchments (e.g. The Lud). The extremely rapid increase in flows following the July 20th rainfall in the Lambourn is very atypical of a Chalk river and has no parallel in the 45-year flow series for the gauging station at Shaw (Newbury).

Testimony to the number of basins subject to extraordinary summer flows in 2007 is provided by Figure 12, which shows estimated daily outflows from England and Wales for 2007. From mid-June to late-July outflows exceeded the previous daily maxima (in a series from 1961) for all but a few days.



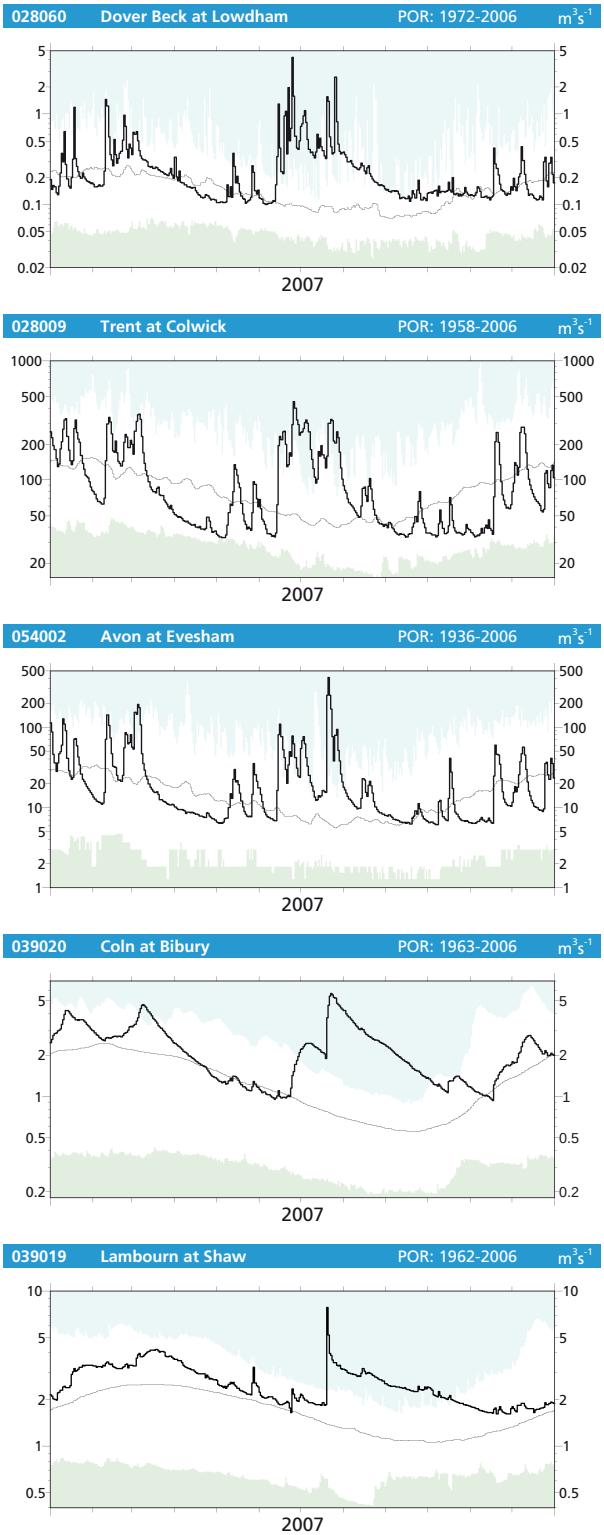
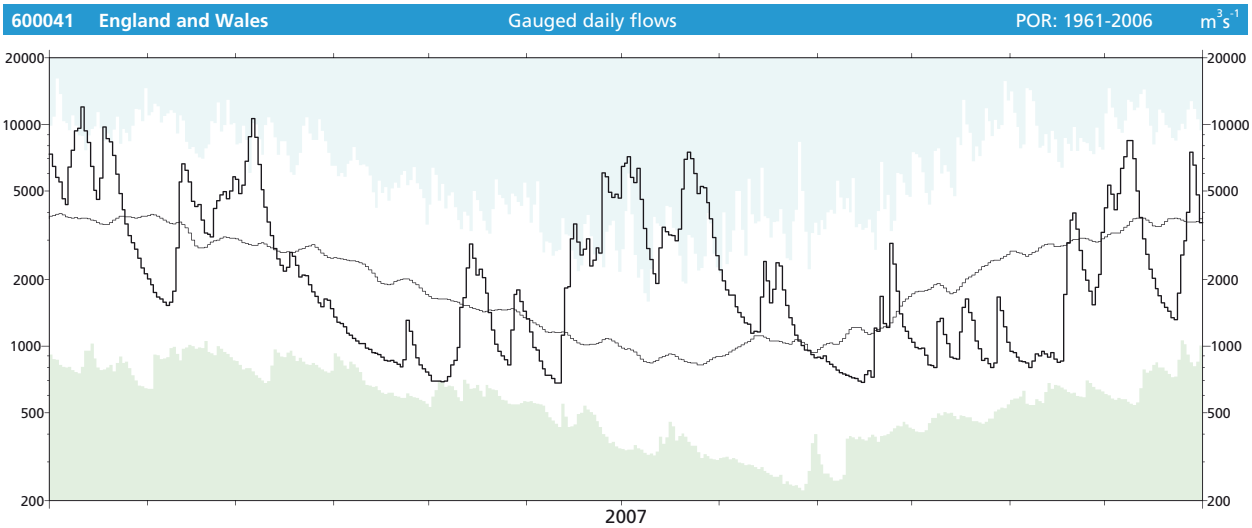


Figure 11: *Daily flow hydrographs for a selection of index gauging stations*

Figure 12: *An index of daily outflows from England and Wales*



Data Source: National River Flow Archive; website: http://www.ceh.ac.uk/data/nrfa/index.html

Rarity of the flood maxima

In the following analyses, flood rarity has been assessed using the rank of the peak level and/or an assessment of the peak flow's probability of occurrence in any given year (expressed as a percentage). The analytical approaches used follow those detailed in the Flood Estimation Handbook.[11] For further details see Appendix I.

Flow measurement

By their nature, extreme flows can be difficult to measure accurately. In many rivers, assessment of the maximum flow in 2007 required considerable extrapolation of the stage-discharge relationship, adjustment to account for backwater effects and/or estimation of the amount of flow across the floodplain. This introduced substantial uncertainty into many flow estimates, compounded in some areas by the very unusual hydraulic conditions encountered during the summer of 2007. In some rivers (Chalk streams in particular) the heavy growth of aquatic plants (typical of the early summer – see Plate 5) reduced the channel capacity in many reaches.
This resulted in higher river levels than would normally occur during a winter flood of similar magnitude, and caused overbank spillage at lower discharge rates than normal. As a consequence, a substantial proportion of the total flow for some rivers was over the floodplain, bypassing gauging stations in many cases (Plate 6).

Plate 5: *Typical summer aquatic plant growth in a Chalk river*

Plate 6: *The Evenlode at Cassington gauging station (up to 40% of the total flow bypassed the station)*

Peak levels and flows

Isolated examples of bankfull flows being exceeded were reported in late May (e.g. the River Thame in Oxfordshire). These heralded exceptional summer flows in mid-June, when previous maximum recorded river levels were exceeded in Yorkshire (e.g. for the Skell) and the Midlands (e.g. the Cole and Witton). Extreme summer flows were even more spatially extensive in late June, when new maximum recorded river levels were established in Yorkshire (e.g. in rivers draining the North York Moors and throughout much of the Don, Calder and lower Aire basins). Peak levels far exceeded previous maxima at some gauging stations: on the Don at Hadfields, for example, the 2007 peak was more than 1.7m above the preceding maximum.[7] Levels in the River Hull remained below bankfull but the city's drainage network was overwhelmed by the extreme rainfall; being very low-lying Hull is particularly at risk from surface water flooding.[7] In the Midlands, the River Teme (at Tenbury), recorded a new maximum flow on the 21st in a series from 1958. To the east, the Penk (Staffordshire) and Idle (Nottinghamshire) also exceeded previous highest levels.

Four weeks later, the June peak on the Teme was eclipsed and new level or flow maxima were common throughout the Warwickshire Avon and upper Great Ouse basin (e.g. at Newport Pagnell), and in the western half of the Thames basin (see Table 5). The Ock was among a number of rivers which exceeded previous maximum levels by a very wide margin and flows in many rivers draining the Cotswolds were at their highest on record. Like the Teme, the Chelt peaked well above the June maximum and outstanding flows were also registered on the Evenlode and Windrush. Contributions from these Cotswold tributaries resulted in a peak level in the upper Thames at Eynsham which was second only to the 1903 flood (based on lock levels). On 21st July, levels in the Warwickshire Avon at Evesham reached their highest in an (incomplete) series from 1848. The outstanding runoff contributed to levels in the lower Severn (at Gloucester Locks), which were closely comparable with the extreme March 1947 peak (see page 23); upstream at Tewkesbury and Saxon's Lode, the 1947 flood level was exceeded.

Sustained high summer flows in groundwater-fed streams and rivers are especially rare. In 2007 however, a combination of record summer groundwater contributions and significant surface runoff saw outstanding flow rates in many spring-fed rivers. New maximum flows were established from the North York Moors to the Berkshire Downs, with remarkable flows characterising many Chalk streams.

Table 5: *Examples of notable peak levels recorded during June and July*

NRFA Station number	River	Gauging Station	County	Maximum level in 2007 (m)	Date	Rank*
27001	Nidd	Hunsingore	North Yorkshire	2.717	26th June	2/72
27006	Don	Hadfields	South Yorkshire	4.675	26th June	1/42
27025	Rother	Woodhouse Mill	South Yorkshire	4.067	26th June	1/46
27030	Dearne	Adwick	South Yorkshire	2.77	26th June	1/44
28027	Erewash	Sandiacre	Nottinghamshire	2.102	26th June	2/42
28085	Derwent	Derby St Mary's	Derbyshire	2.809	26th June	2/25**
33018	Tove	Cappenham Br	Northamptonshire	1.89	21st July	2/45
39008	Thames	Eynsham	Oxfordshire	1.187	24th July	1/56
39026	Cherwell	Banbury	Oxfordshire	2.392	20th July	2/41
39027	Pang	Pangbourne	Berkshire	c.0.75	26th July	1/39
39081	Ock	Abingdon	Oxfordshire	1.8	22nd July	1/45
54032	Severn	Saxons Lode	Worcestershire	5.925	22nd July	1/37
54036	Isbourne	Hinton on Green	Gloucestershire	4.93	20th July	1/35

* Ranking relates to the number of years of record.
** Ranks 4/73 if series extended using Longbridge Weir levels.

Probability of occurrence

Table 6 provides assessments of the probability of occurrence of the peak flow estimates for a selection of rivers in the worst affected areas. The peak flow data have been provided by the Environment Agency and, in many cases, are subject to future review as more information, or more detailed analyses, become available. The estimates are commonly well beyond the range of the highest current meter gaugings but some take account of high flow measurements undertaken by Acoustic Doppler Current Profilers (Plate 7) or by assessments based on hydraulic models. In a few cases these contemporary assessments have significantly lower uncertainty than earlier flood events (e.g. when assessments of floodplain flows were rudimentary). The peak flows, and the associated probabilities, have generally been rounded to avoid any assumption of unwarranted precision.

Plate 7: *Flow measurement using an Acoustic Doppler Current Profiler in the river Thames (July 2007)*

Probabilities of <2% are associated with many of the featured flood peaks and a significant proportion are more extreme. Considering peak flows on major rivers, the rainfall, river level and flow evidence suggest that the floods on the Warwickshire Avon and the Don were among the most outstanding. At Evesham, the April 1998 peak, ascribed a 1% probability in a contemporary analysis,[12] was exceeded by nearly 50 m^3s^{-1} in July 2007[‡].

A greater degree of uncertainty is generally associated with probabilities derived using flow records of shorter durations and, in some cases, historically well documented floods are known to be of a greater magnitude than contemporary peaks. The River Lud provides an extreme example: the June and July 2007 peaks both exceeded previous maxima in a gauged series from 1968. However, estimated peak flows during a catastrophic flood in 1920 were an order of magnitude greater.[13]

More extreme events than those listed in Table 5 will undoubtedly have occurred where gauging stations were overwhelmed in the summer of 2007 and in ungauged streams and rivers whose headwaters coincided with the most intense rainfall during the summer storms (e.g. in the southern Pennines and parts of the Cotswolds).

Away from the wettest areas, the maximum flows registered in 2007 were often extreme in relation to typical summer floods, but not exceptional by comparison with major winter events. For example, the Thames at Kingston registered its highest summer (June-August) daily flow since 1903. Notwithstanding extreme headwater flows, however, the peak flow in July 2007 does not rank among the top 80 floods for the Kingston gauging station – which has a flow record from 1883.

[‡] When both events are included in the probability analysis, the rarity of both events is reduced.

Table 6: *Peak flows and estimated probability of occurrence for selected rivers during the 2007 summer floods*

NRFA Station Number	River	Gauging Station	County	Period of Record	Date	Flow (m^3/s)	Prob of Occ (%)*
Event 1							
28066	Cole	Coleshill	West Midlands	1973-2007	14th June	38.8	2-1
27086	Skell	Alma Weir	North Yorkshire	1984-2007	14th June	106	1-0.66
Event 2							
27021	Don	Doncaster	South Yorkshire	1959-2007	June	350	< 0.5
27079	Calder	Methley	West Yorkshire	1988-2007	June	374	4-2
27080	Aire	Lemonroyd	West Yorkshire	1985-2007	June	248	6.66-3
29001	Waithe Beck	Brigsley	Lincolnshire	1960-2007	25th June	7.9	1-0.66
29003	Lud	Louth	Lincolnshire	1968-2007	25th June	14.5	< 0.5
28015	Idle	Mattersey	Nottinghamshire	1982-2007	26th June	20.1	5-2
28049	Ryton	Worksop	Nottinghamshire	1970-2007	25th June	17.2	1.25-1
Event 3							
33037	Bedford Ouse	Newport Pagnell	Northamptonshire	1969-2007	21st July	95	12.5-8.33
33057	Ouzel	Leighton Buzzard	Bedfordshire	1976-2007	20th July	15	4-3
54002	Avon	Evesham	Warkwickshire	1936-2007	21st July	464	1-0.66
54008	Teme	Tenbury	Shropshire/ Worcestershire	1956-2007	21st July	263	5-2
54023	Badsey Brook	Offenham	Worcestershire	1969-2007	20th July	160	<0.5
39019	Lambourn	Shaw	Berkshire	1962-2007	21st July	9.9	<0.5
39034	Evenlode	Cassington Mill	Oxfordshire	1970-2007	July	70	1.25-1†
39046	Thames	Sutton Courtenay	Oxfordshire	1973-2007	July	200	10-2.5

* The percentage probability of occurrence in any one year.
† Based on gauged flows and modelling evidence.

Groundwater

Except under rare circumstances (e.g. during the winter of 2000-2001), groundwater is not a major contributor to fluvial flooding. This is particularly true in summer – the aquifer recharge season normally terminates in the spring and recessions in groundwater levels are generally well established by the early summer. In a typical summer, water-tables then remain depressed until well into the autumn.

In early 2007, groundwater levels in most areas were seasonally low following extended drought conditions.[6] Levels generally recovered through the late winter but the seasonal recessions began early in 2007 and were notably steep in April. By late May, however, exceptionally wet soil conditions allowed appreciable local infiltration to occur.[6] Some of the most outstanding rainfall totals recorded during the June and July storms coincided with outcrop areas of the major aquifers – the Jurassic and Carboniferous Limestones and parts of the Chalk

especially. The sustained summer rainfall generated a major pulse of aquifer recharge, followed by notable rises in groundwater levels in a number of index wells and boreholes across eastern, central and southern England.

The impact of the summer recharge in 2007 may be seen in Figure 13, which shows groundwater level hydrographs for eight index wells and boreholes in outcrop areas subject to the heaviest summer rainfall. Each hydrograph shows groundwater levels (mostly recorded at weekly or monthly intervals) together with the highest (upper green envelope) and lowest levels in the pre-2007 record. Three-year hydrographs are featured in order to illustrate the important antecedent recharge patterns.

The summer recharge triggered remarkable increases in groundwater levels in a number of major aquifers. Levels have been routinely measured since 1889 at Dalton Holme in the Chalk of the Yorkshire Wolds and only in 1912 and 1969 have summer levels approached those recorded in 2007. For wells and boreholes in the Chalk with shorter records, new late-summer maximum levels were common: for example, at West Woodyates Manor (Dorset), Rockley (Wiltshire) and Washpit Farm (Norfolk). Summer maxima were much less outstanding at Stonor in the Chilterns and, generally, groundwater level recoveries were considerably more muted in the Chalk of the South East where the summer rainfall was relatively moderate.

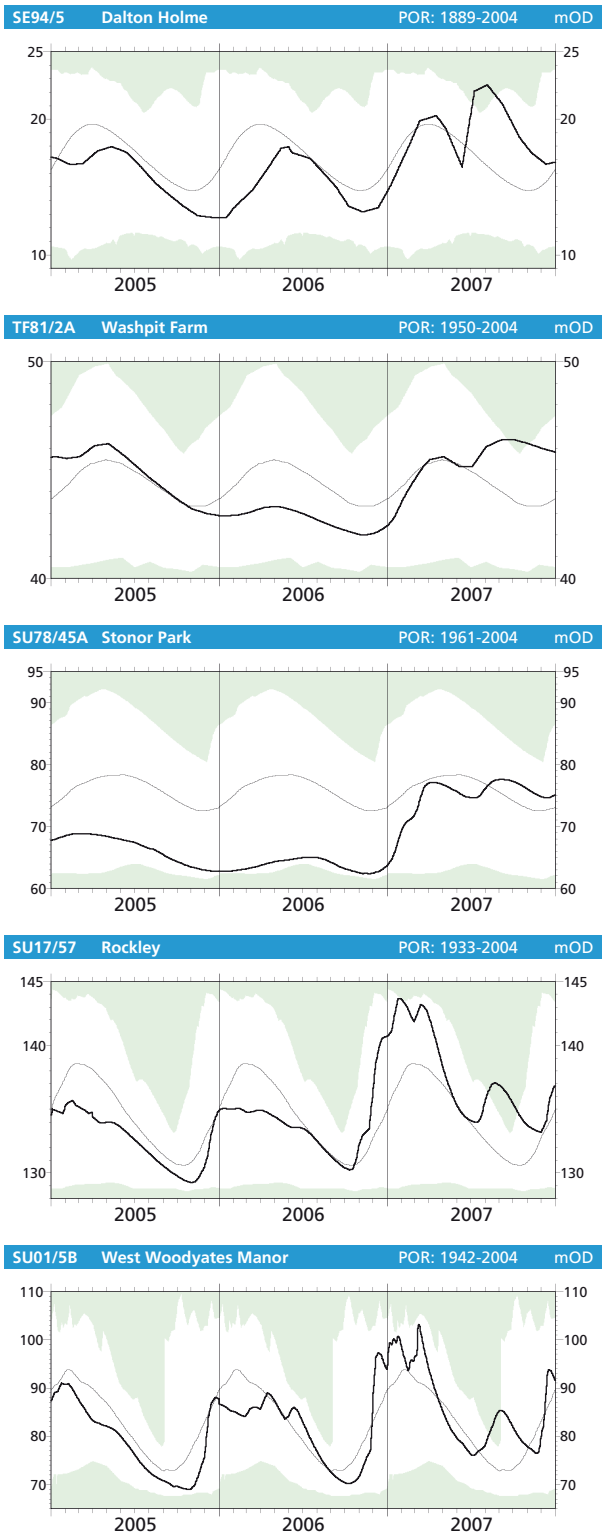
In the Jurassic Limestone of the Cotswolds, late July groundwater levels at Ampney Crucis substantially exceeded the previous highest recorded summer level in a 50-year series. Notably high 2007 summer maxima were also registered in the Lincolnshire Limestone (see the New Red Lion hydrograph) and in the Carboniferous Limestone at Alstonfield (Derbyshire). In the characteristically slow-responding Permo-Triassic sandstones of the Midlands, summer 2007 groundwater levels were generally unremarkable; a reflection of the depressed levels early in the year - following protracted drought conditions in 2004-2006.

The seasonally extreme groundwater levels were reflected in greatly increased summer outflows from springs and seepages. These contributed to major lowland flood peaks and, particularly, to the extended period of record-breaking late-summer river flows in permeable catchments.

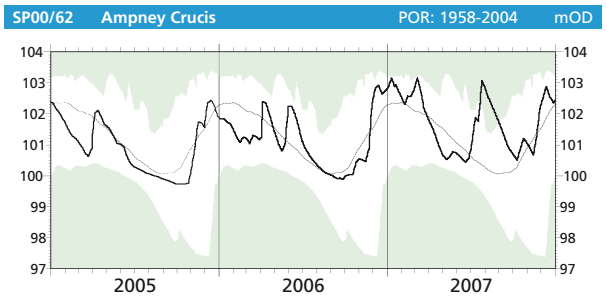
In those areas subject to the heaviest summer recharge, the normal autumn recovery in recharge rates was expected to begin with groundwater levels already well above the normal seasonal range. Correspondingly, there was a considerably enhanced risk of groundwater flooding in the winter of 2007-2008. A preliminary analysis, undertaken in the late summer, suggested that even with average rainfall through the autumn and early winter, there was a significant risk of groundwater flooding in the vulnerable parts of the Chalk outcrop.[9] Fortunately, England and Wales experienced its second driest August-October period since 1978, which allowed groundwater level recessions to be re-established, substantially reducing but not eliminating the risk of groundwater flooding through the winter.[14]

Figure 13: *2005-2007 groundwater-level hydrographs*

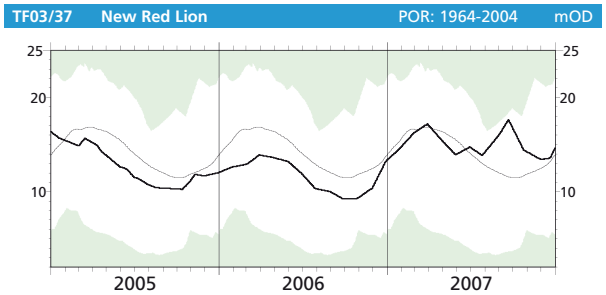
Aquifer: *Chalk*



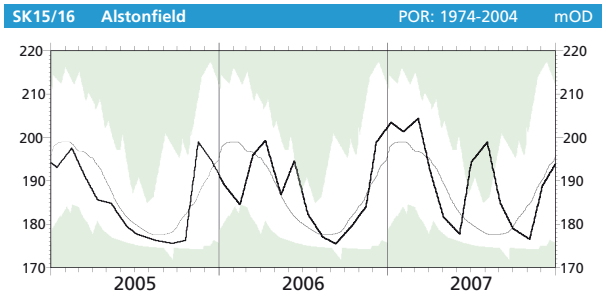
Aquifer: *Middle Jurassic*



Aquifer: *Lincolnshire Limestone*



Aquifer: *Carboniferous Limestone*



Impacts of the flooding

This report is primarily a hydrological appraisal of the 2007 flooding but any assessment of its magnitude would be incomplete without an overview of its impact on the community and the aquatic environment.

Societal impacts

For most of those directly affected, the scale of the flooding was beyond anything experienced in their lifetime. Fourteen fatalities were linked to the flooding and many thousands of people suffered prolonged misery as a result of floodwater inundation – sometimes repeatedly – of their properties. Over 55,000 homes and 6,000 businesses were flooded;[7] the related insurance claims were approaching £3 billion by late-2007. Many flooded and low-lying localities had to be evacuated and an assessment by the emergency services suggests that the summer of 2007 saw the greatest number of search and rescue missions in this country since the Second World War.

The worst affected areas were in northern England (particularly urban areas in South Yorkshire and Humberside), the south Midlands and parts of the upper Thames basin. Significant flood damage was, however, reported from areas as far apart as County Tyrone and Norfolk.[6] Flooding affected more than 300 schools in Yorkshire and Humberside and structural damage to transport and utility infrastructure was common; over 100 sewage treatment works in the Midlands were affected. In Gloucestershire, flooding of the Mythe Water Treatment plant left over 300,000 people relying on bottled water for several weeks[7] and power supplies for over 40,000 homes were interrupted while temporary flood defences were installed at an electricity sub-station. Near Rotherham, the threat of failure of the Ulley Dam following the late-June rainfall was a primary factor in the evacuation of around 1,000 people.

Commercial activities were badly affected in many towns and cities. In Sheffield, for example, the Meadowhall shopping centre was closed for a week in late June[7] and there were significant local impacts on tourism. The cancellation of late-summer hotel bookings in Oxford was exceptionally high. The extensive floodplain inundations caused widespread damage to maturing crops – mostly wheat, barley and fodder – and required the removal of livestock to higher ground (e.g. in Gloucestershire and Lincolnshire). Disruption to road and rail transport was very extensive and sustained, exacerbated in many localities by landslides, local power failures and, in July, by the coincidence of the heaviest rainfall with the additional traffic volumes which normally accompany the end of the school term.

Ecological impacts

Floods are a natural phenomenon and, on rare occasions, their impact on the community can be devastating, but spate conditions are also very important to our natural environment. Small floods, for example, stimulate fish migration and clean river gravels of silt, whilst larger floods inundate floodplains, naturally enriching the soil with fertile silt, providing habitat for wading birds and spawning sites for fish. Even extreme floods play a crucial role in shaping our landscape and removing debris from our rivers; whilst they may destroy some habitats, they also create new ones[f]. Some rivers that suffer erosion during floods may recover their size and shape within a few years, particularly lowland rivers where sediments are

easily reworked by lower flows. In upland rivers, larger rocks and boulders may only be moved during large floods and so channel changes may persist; for example, some channel features formed during the Lynmouth floods of 1952 are still much in evidence today.

To be most ecologically beneficial, floods need to occur at the right time to fit in with the life history of British plants and animals. The summer floods of 2007 inundated the nests of birds (such as redshank and snipe) on floodplains that are usually dry at this time of year and created high flow velocities in rivers, drowning small mammals and sweeping many young fish downstream as they were unable to swim against strong currents. Many adult fish became stranded on inundated floodplains, such as the River Severn; certain species that spawn naturally on the inundated floodplain (e.g. bream) were hindered in some areas from returning to the river by embankments as the floods receded – significant numbers of fish needed to be rescued by wildlife conservation staff.

Fish fry numbers and their survival to adulthood (recruitment) varies naturally from year to year. Because of the floods, 2007 is likely to be a poorer than average year for fish recruitment, but previous years, such as 2003, were good years, so adult fish numbers may not be impacted in the long term. The impact will vary between species; fish such as chub that live for 20 years may be less impacted than for those such as dace that only live for three-four years. Impact variations will also reflect the characteristics of individual rivers; natural rivers have complex shapes with many pools and backwaters that provide refuge for fish away from strong currents. In contrast, engineered rivers often have a more regular shape (such as a trapezoidal cross-section) which provide little refuge; correspondingly flood impacts may be greater.

The summer flooding in context

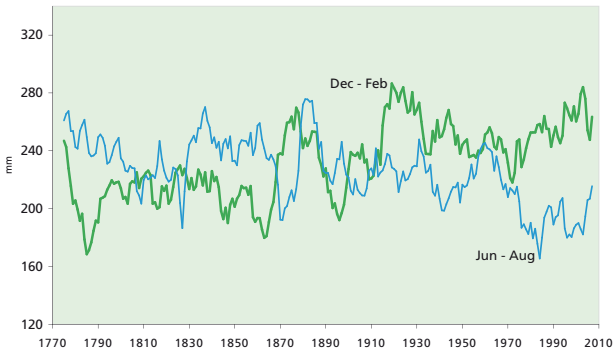
Summer floods in England and Wales

Few UK summers pass without some localised or catchment-scale flooding but widespread floodplain inundations have been very uncommon in the June-August period during the last 100 years. Notable but short-lived flooding was registered across much of England and Wales following the passage of Hurricane Charley in August 1986[15] with exceptional flows in many Pennine and Welsh rivers. The summer half-year of 1968 provides a more convincing parallel with 2007. Severe flood episodes occurred in July and September; rainfall totals of >100mm (on the 17th-18th) during the latter month were more extensive than in the summer storms of 2007.[16]

Further examples of major summer flooding in England may be found in the historical record. These include 1912, when severe flooding affected large parts of eastern and central England, and 1903 when steady but continuous rainfall[17] generated widespread flooding across southern England, in the Thames basin particularly. Southern Britain also suffered widespread floodplain inundations in July 1875 and July 1853.[18] As can be seen in Figure 14, wet summers were more common prior to the 20th century, when rainfall totals for the June-August period were often greater than for the winter (December-February).

Every major flood episode has a unique spatial footprint, making assessments of their relative magnitude difficult, particularly at the national scale. Estimates of daily runoff from England and Wales do, however, provide a broad basis for comparison. These clearly indicate that outflows during the summer of 2007, although having no close modern precedent (see Table 4), were exceeded during a number of widespread winter flood events in the last 20 years (including 2000, 1995 and 1990). However, the impact of the 2007 flooding on well-populated floodplains and many, widely distributed, urban centres ensured that the effect on the community was greater than the hydrological magnitude alone might imply. Partly as a consequence, this led to comparisons with the benchmark flooding of March 1947.

Figure 14: *England and Wales winter (Dec-Feb) and summer (Jun-Aug) rainfall (10-year running means)*



[f] *Although specific areas have been designated for wildlife preservation, such as nature reserves, they are insufficient to permit natural habitats to be destroyed without significant ecological damage; thus in a managed environment like that of the UK, floods can be seen as destructive.*

The 1947 flood

Whilst similar in extent in a few regions, the 1947 flood was entirely different in character and substantially greater in both magnitude and impact to the flooding experienced in 2007.

In late February 1947, following an exceptionally severe winter, a sequence of severe blizzards left snow cover of 50-120cm across much of the England and Wales. Extremely extensive flooding was initiated on 12th March by heavy frontal rainfall and an associated steep rise in temperature. This triggered a rapid thaw over still-frozen ground.[19] With relatively few flood defences, poorly maintained drainage systems (many blocked by ice) and significant rainfall on almost every day until 4th April, floodplain inundations were extensive and protracted throughout most of Britain (although the thaw was delayed until April in the north).

The floodwaters greatly exacerbated the late-winter transport difficulties – many roads and some sections of the rail network were impassable. Widespread power cuts, many associated with the inability to mine or move coal from the ports, were especially disruptive.[20] Inundation of water treatment and sewage works produced water supply and sanitation problems across the country. These represented a serious threat to public health; in the Thames Valley alone an estimated one million people were without water, the majority in east London. The flooding caused the shut-down of many hundreds of factories (some already on short-time due to the power cuts).

Frosts destroyed much of the late potato crop and, following the flood, access to farmland was impossible over much of the country.[20] With spring sowing postponed in many areas, a Commonwealth Disaster Fund was launched to help alleviate the misery; the food supply outlook was particularly bleak and field stations – some catering for >20,000 people – were established across England and Wales.

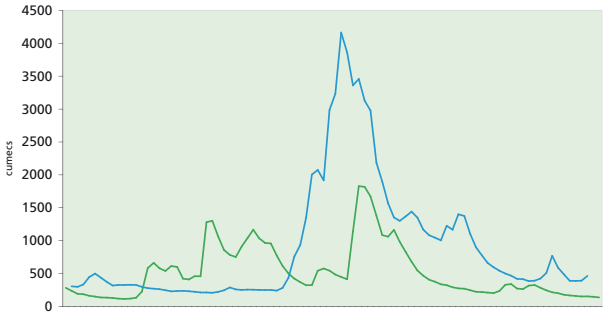
In some areas, including the lower Severn valley (Plate 8), peak flows in 2007 were comparable to, or exceeded, those registered in 1947 but the latter event was substantially more severe at a national scale. A broad index of the relative magnitude of the two flood events can be derived using the combined flows for eight gauging stations monitoring contemporary flows in major rivers in England and Wales, as shown on Figure 15.

At its peak, the 1947 flood generated flows that were more than twice the maximum for the summer of 2007. If an economic rather than hydrological focus is used, then the contrasts are less compelling as floodplain development over the last 60 years have greatly increased the financial impact of major floods.

Plate 8a: *The Plough, Upton on Severn, July 2007*

Plate 8b: *The Plough, March 1947*

Figure 15: *A comparison of flows for the Feb-Mar 1947 (blue trace) and June-Aug 2007 periods*



Climate change

A series of major flood episodes in the early years of the 21st century has fuelled speculation that flood risk is increasing due to global warming. By their nature however, any cluster of extreme hydrological events cannot readily be linked to climate change. If they form part of a developing pattern or emerging trend, then a causative association becomes more plausible. Over the last 30-40 years, positive trends in a number of high river flow indicators (e.g. flood frequency, 30-day maxima) have been identified[21,22,23] and increases in intense rainfall have been observed over a similar period.[24,25] Generally, these studies have shown the most pronounced changes in the more maritime northern and western areas of the UK, and these have been related to changes in atmospheric circulation patterns which typically affect winter precipitation.[24]

Long-term trends in flood maxima

Substantial temporal variations in both flood frequency and magnitude are a common feature of many lengthy river flow time series in England and Wales. There were, for example, relatively few notable flood events in the 1960s and early 1970s. This period coincided with rapid growth in the UK gauging station network, and the contrast with the relatively 'flood rich' recent past may have contributed to a perception that flood frequency and magnitude are increasing. Over longer timespans this perception becomes much weaker and there is little compelling evidence for long term trends in flood magnitude for rivers in England & Wales.

The summer 2007 floods can be examined in a lengthy historical context using very long flood series for the Warwickshire Avon and the Thames (where extreme flows in 2007 were largely restricted to the western tributaries). The Thames flood series is based on recorded water-year maximum flows, whilst that for the Avon combines water-year maxima from 1937 (the beginning of the formal river flow record) and earlier assessments of flood flows based on systematically recorded peak level data for notable events.[12] The two series are plotted in Figures 16 and 17. For the Avon, the two highest floods on record occur in the last 10 years, but no overall increase in flood magnitude is readily apparent; the same lack of long-term trend (over a shorter timespan) is evident for the Thames. This is despite a significant increase in temperature and substantial changes in seasonal rainfall patterns since the middle of the 19th century (see Figure 14).

Figure 16: *Flood events on the River Avon*

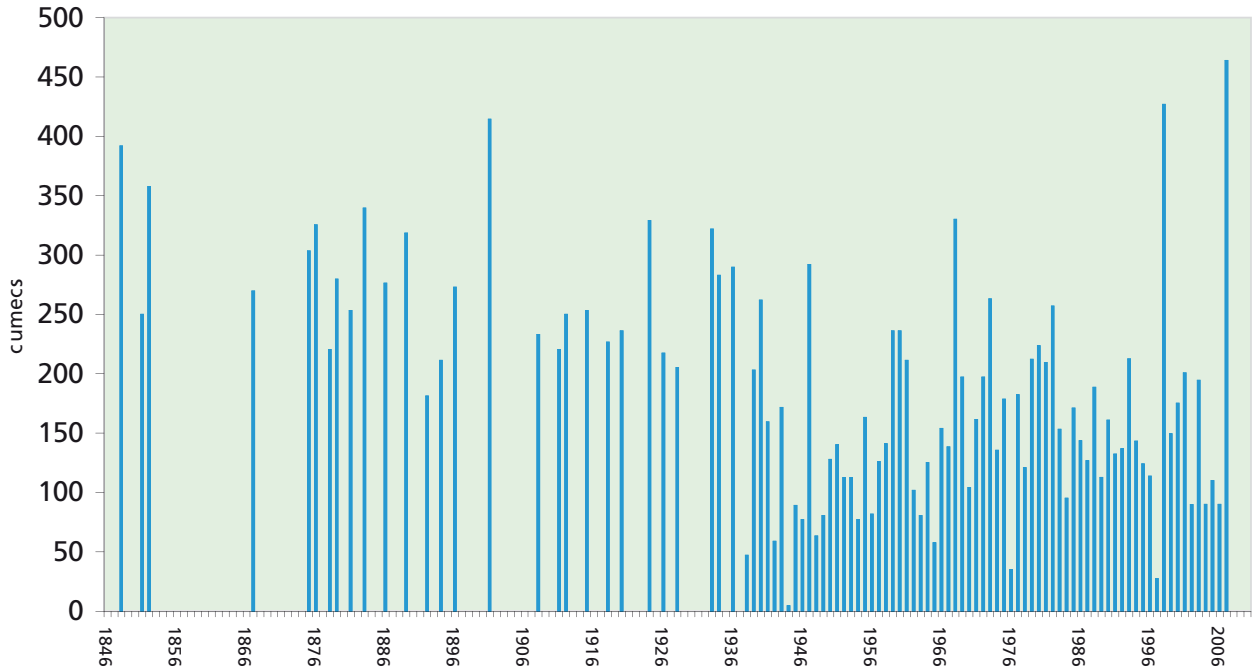
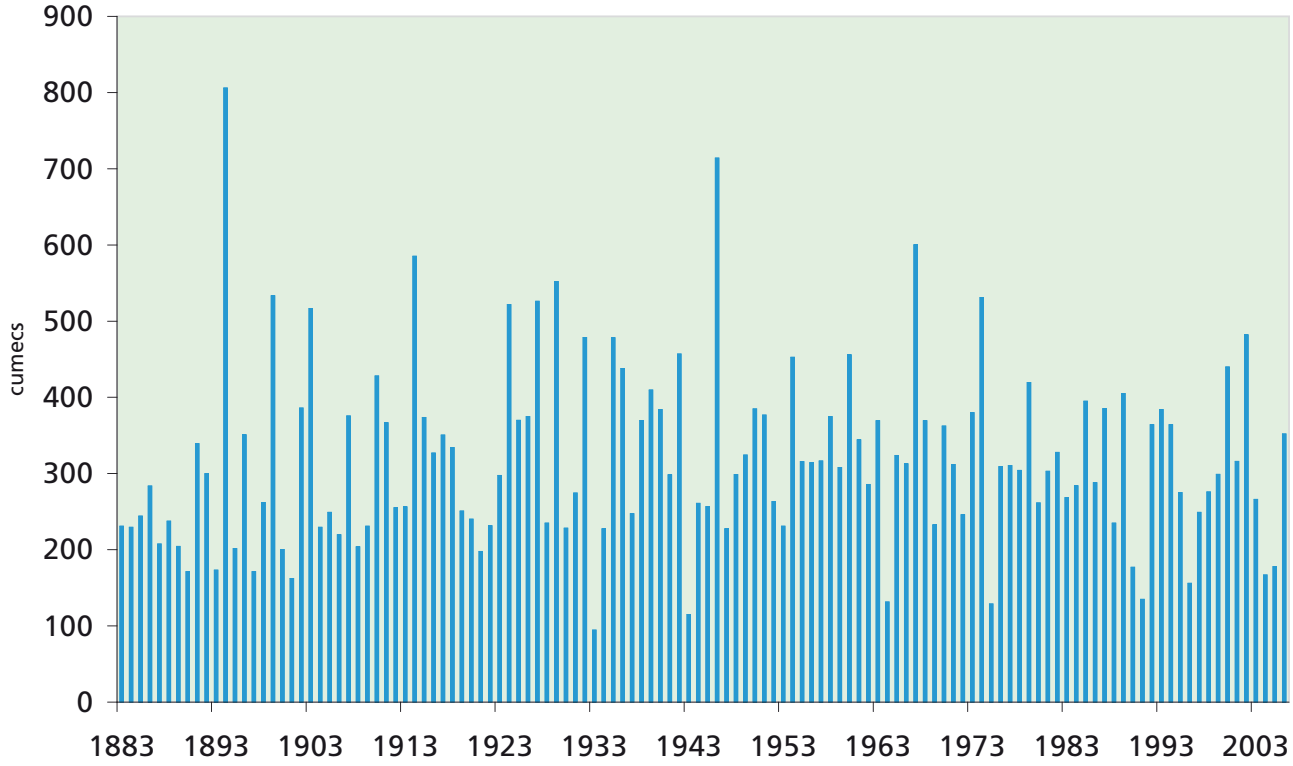


Figure 17: *Water-year maximum flows for the River Thames*



Global warming and flood risk

The association between rising temperatures and flood risk is complex. In a warming world, the risk of tidal flooding is increasing (as sea levels rise) but there is considerable uncertainty about future changes in the frequency of extreme rainfall events. A number of recent climate modelling studies have predicted that such events are likely to become more frequent in the UK[26,27] – particularly during the winter – but the proportion of summer rainfall falling in intense storms may also increase. Worldwide climate modelling studies also suggest an increase in rainfall intensities, particularly at middle and high latitudes[28] and some studies have identified a possible increased risk of summer flooding.[29] If realized, such scenarios would have major implications for flood risk management and engineering design. A greater frequency of extreme rainfall events would certainly increase the risk of localised flash flooding – with associated drainage problems, particularly in urban areas.

Whilst catchment modelling studies suggest that predicted precipitation changes may result in increased fluvial flooding in some UK catchments, current assessments of potential future impacts in the UK are spatially variable and subject to considerable uncertainties.[30] It is important also to recognise that the impact of global warming on UK fluvial flood risk is unlikely to be entirely malign. Observational evidence indicates that an interplay of factors may imply a lower sensitivity to climate change. As winter temperatures have increased, snowmelt (a primary cause of the 1947 flood and a significant proportion of major historical floods) has declined as an exacerbating factor.[31] Warmer, drier summers could also be beneficial: the resulting very dry soil conditions could help to moderate fluvial flood risk by restricting the length of the winter flood season.[32]

The 2007 floods serve to emphasise the capricious nature of the UK climate which, on rare occasions, can result in extreme hydrological conditions. Overall summer rainfall in 2007 was anomalous in relation to both favoured climate change scenarios and to recent tendencies in rainfall patterns – summers over the last 30 years have tended to be drier than average and a modest decline in the proportion of summer rainfall falling in intense events has been identified.[24] However, whilst observational evidence of a higher frequency of intense summer storms is as yet lacking, storms of the type which triggered the very damaging flash flooding in 2007 may form part of a future climate regime.[28]

Flood risk and vulnerability

Changes in vulnerability to flooding during the 20th century cannot be attributed primarily to climatic variability or change. Continuing floodplain development and urban growth has contributed to the rapidly rising economic costs of notable flood events. At the same time, and particularly over the last 50 years, improvements in river management (e.g. channel re-profiling and re-alignment, more efficient weir design) have increased the capacity of many river channels. As a consequence flows in the lower Thames, for example, which would have caused substantial floodplain inundations in the 1940s can now be readily contained within bank. Such developments, together with other flood alleviation measures and improved forecasting capabilities[7] have significantly moderated the impact of major flood episodes.

Concluding remarks

The 2007 flooding was remarkable in its extent and severity, and truly outstanding for a summer event. Widespread flooding was inevitable given the magnitude and intensity of rainfall which has no close modern parallel in the summer. Many areas experienced a wide range of flood types, from the local effects of surface runoff to extensive floodplain inundations. A distinguishing feature was the very high proportion of properties and commercial premises inundated by non-fluvial flooding. In the worst affected areas, the rainfall and river flows were of a greater magnitude than the design limit of some flood alleviation schemes and many urban drainage systems.

The flooding underlined the UK's continuing vulnerability to climatic extremes. However, long-term rainfall and river flow records confirm the exceptional rarity of the hydrological conditions experienced in 2007. Climate change scenarios indicate that summers may become both warmer and drier; rainfall patterns may also become more variable with an increased frequency of intense storms. But considerable uncertainty attends such scenarios, especially in relation to extreme rainfall events. A synthesis of the rainfall and river flow evidence indicates that the summer was a very singular episode. The associated fluvial flooding does not constitute an element in any established hydrological trend or appear to form part of a pattern consistent with currently favoured climate change scenarios.

The need to identify significant hydrological trends, and the escalating costs of contemporary flood episodes, reinforces the need to maintain the UK's hydrometric monitoring capabilities – particularly in relation to extreme flows. This capability will be crucial if climate change scenarios and observational evidence is to become more closely reconciled, thus providing a firm platform for the design of future flood alleviation strategies.

Flooding is a natural process and cannot be prevented but the impact of floods can be moderated. Ongoing research into the factors which influence long-term variations in flood frequency and, more challengingly, how global warming may impact on flood risk in future, provides the foundation for more effective forecasting of flood episodes.

Similarly, greater understanding of how catchments respond to extreme rainfall underpins the design of better flood alleviation strategies. One manifestation of this is a decreasing reliance on engineered defences (which still have a very important role) and a corresponding focus on catchment-wide flood risk management. This seeks to exploit, rather than compromise, the natural ability of the floodplain to accommodate floodwaters. Such advances, allied to other adaptive strategies,[33] including an increasing alertness of those exposed to flood risk, would increase resilience to what remains a continuing threat. Strengthening resilience is essential since, even with stable climatic conditions, the need for effective flood mitigation measures will not diminish.

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APPENDIX I

Methodology for estimating the probability of occurrence of flood events

The objective of flood frequency analysis is to establish a functional relationship between the magnitude of peak flows and the associated annual probability of exceedance (or return period) for a particular catchment. In the UK, the standard procedures for flood frequency analysis are described in the Flood Estimation Handbook (FEH). The particular method used in this study is based on direct statistical analysis of annual maximum series (AMS) of instantaneous peak flow measurements obtained from river gauging stations.

The relationship between peak flow magnitude and probability is established by fitting a statistical distribution to the AMS and using this distribution to predict either the probability of observing an event of a particular magnitude in any one year, or to establish the probability associated with the maximum flow of a real event, as is the case in this study.

If a flood frequency analysis is conducted using a long flow record, the analysis can be based on this record alone (single site analysis). The FEH recommends that single site analysis should only be used to analyse and predict floods with a return period of less than half the record length and that a minimum of 14 annual maximum events should be available. While the FEH guidelines were derived to assist users in choosing the most appropriate method, the use of shorter record lengths does not invalidate the results obtained from a single site analysis, but the final results will be associated with larger uncertainty than if a longer record was available.

Given the relatively short duration of most flow recording stations, it is rare that single site analysis alone will be sufficient. It is normal practice to therefore include (or pool) additional data from other gauging stations from catchments considered hydrologically similar to the target catchments. The pooling group is defined according to 'hydrological similarity' defined in the FEH in terms of catchment area, standard annual average rainfall for the period 1961-1990 and a baseflow index defined according to HOST soil types (http://www.ceh.ac.uk/data/feh.htm). The gauged catchments identified as being the most similar to the target catchment are ranked according to the degree of similarity, with the most similar being assigned as rank one in the pooling group.

The FEH generally recommends using the pooled analysis over the single site analysis; it is worth noting however that, based on a series of Monte Carlo experiments, it has been shown[1] that while pooled analyses might perform better for a region on average, single site analysis might still be the preferred option for individual catchments.

For the percentage probabilities quoted in this study, both single-site and pooled analyses were conducted, and the figures quoted reflect a compromise between the two approaches. More credence was given to the results for pooled analysis for the shortest records, but for the longer (>30 years), the single site results were given greater weight. Some analyses, using both single-site and pooled approaches, resulted in very low probabilities (<0.2% for any given year). Such figures are subject to very high uncertainties and potentially misleading, so in this report these very low probabilities are quoted as being < 0.5 (equivalent to a return period of > 200 years). As the aim of this report is to provide indicative probabilities based on preliminary data, wide ranges are often quoted (e.g. 1-0.66%) to reflect the difference between the single site and pooled approaches, and the high degree of uncertainty associated with the estimates (see below).

By fitting a single statistical distribution to an AMS of peak flow, it is automatically assumed that the individual flood events in the AMS are all generated from the same underlying flood generating mechanism. While this is likely to be a reasonable assumption for most catchments, concerns have been raised with regards to the modelling of AMS of peak flow from permeable catchments. A correction procedure for permeable catchments is outlined in the FEH, but this has not been applied in the present study.

Data

The FEH statistical method for flood frequency analysis is based on annual maximum series (AMS) of instantaneous peak flow measurements. An AMS of peak flows is constructed by identifying the maximum peak flow value observed in each particular 'water year'. The Environment Agency has extracted and quality checked AMS for 982 catchments located throughout the UK and made these data publicly available through the HiFlows-UK web site (http://www.environment-agency.gov.uk/hiflowsuk/).

In this study, the Hiflows Data UK series, which generally extends up to 2002, were used, updated to the water-year of 2005-06 using data from the National River Flow Archive. For the water-year of 2006-07 (i.e. the 2007 flood peak), data were obtained from the various regional offices of the Environment Agency. It should be noted that many of these values are provisional estimates and will be subject to further refinement.

One limitation to the pooled analyses is that data could only be updated with the 2007 peak for the stations featured in this report. Consequently, in pooled analyses, the target site features the 2007 maximum, but corresponding maximas will not feature in the station flood series used for pooling. This is a necessary result of assembling limited amounts of data over a short timescale. Pooled analyses conducted using a fully-updated national dataset – possibly complemented by catchment-based rainfall-runoff, or hydraulic, modelling – may yield different results.

Uncertainty

As flood frequency analysis is often concerned with the prediction of future extreme floods or the analysis of floods larger than any previously observed (in the AMS), the predictions will be associated with a degree of uncertainty. In hydrological modelling, the error sources contributing to the total uncertainty can, in principle, be divided into three sources: observation errors, sampling errors and modelling errors. In practice, however, it is not always possible to attribute the uncertainty to a particular error type. In terms of observation uncertainty, the problems associated with field measurements of extreme floods, such as the summer 2007 event, has already been discussed in this report (see page 16). The homogeneity of the AMS series can also influence the uncertainty in the probability assigned to extreme floods, particularly where advances in gauging techniques or the application of hydraulic models allow floodplain flows to be estimated more effectively than in the past.

In addition, the occurrence of relatively 'flood rich' or 'flood poor' periods in most flood time series implies that probabilities of occurrence can be very sensitive to the length of record used in the analysis.

When considering flood flow, and in particular extreme flow of a magnitude rarely found in the observed systematic records, the uncertainty associated with extrapolation from the rating curve becomes an important error component to consider. Sampling error results from limited data availability (typically dependent on the record length and the degree of extrapolation outside the range of the observed data) and can be estimated using traditional techniques available from the statistical literature or using specialist methods.[2] Model error is the error introduced into the analysis because the particular hydrological model is only a simplified representation of the more complex real-world system under consideration. A full numeric assessment of the uncertainties associated with the flood probabilities featured in this report is beyond the scope of the present study.

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