The 2000/01 Floods
a hydrological appraisal

2nd Edition

Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

British Geological Survey
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Preamble

This report on a flood episode which has established a major new UK hydrological benchmark, is presented in eight components and complements material featured in the Hydrological Review of 2000 and in the monthly Hydrological Summaries of the UK issued as part of the National Hydrological Monitoring Programme (for further details please visit: http://www.ceh.ac.uk/data/nrfa/nhmp/nhmp.html). The Hydrological Summaries provide more detailed coverage of the development and extent of the flooding through the autumn and winter of 2000/01. A map gives the location of most hydrometric monitoring sites mentioned in the report; for other gauging stations reference should be made to the UK Gauging Station Network which provides access to details of all primary gauging stations in the UK.

Acknowledgements

Some of the material for this report was assembled as part of an examination of the autumn 2000 flooding funded by the Department for the Environment, Food and Rural Affairs (under the joint DEFRA/Environment Agency research programme on flood defence). Extensive additional data was furnished by the Environment Agency, Scottish Environment Protection Agency and the Rivers Agency in Northern Ireland. Rainfall data and other climatic information were provided by these measuring authorities and by the Met Office (for historical comparisons of England and Wales rainfall totals, the homogenised national series developed by the Climatic Research Unit and updated by the Hadley Centre has been used).

A report of this type would not have been possible without the help of many individual field and office personnel; their assistance is gratefully acknowledged.

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Introduction and Overview

The extensive flooding across the United Kingdom during the autumn of 2000 and the winter of 2000/01 was the most severe flood episode, on a nationwide scale, since the flooding which followed snowmelt in March 1947. Unprecedented rainfall, over periods extending beyond eight months in some regions, resulted in the redefinition of high flow regimes over wide areas and a substantial extension of the range of recorded groundwater levels. This report documents the flooding within a hydrological framework and concentrates on the period from September to December 2000, but it also addresses the remarkable groundwater conditions which characterised the winter and spring of 2000/01.

Rainfall during the latter half of September 2000 greatly reduced the capacity of soils to absorb further rainfall and, in most areas, the autumn-winter 2000/01 floods were a response to sustained frontal rainfall on near-saturated catchments. Frequent pulses of heavy rain continued through October, November and December, with the result that many new local and regional rainfall records were established across the country. England and Wales experienced its wettest autumn (September to November) on record and the September-December period established a new four-month rainfall maximum in the national rainfall series, which begins in 1766[1].

The heavy and widespread rainfall generated many record river flows. A significant number of individual peak flows had return periods of greater than 100 years and autumn/winter runoff totals exceeded previous maxima (often by wide margins) for the majority of gauging stations in England and Wales. Prolonged high flows sustained flooding over long periods in many catchments. A serious aggravating factor in several areas - the South-East especially - was the frequency of significant flood events; in some impermeable catchments six, or more, floodplain inundations occurred over a 13-week period.

The 2000/01 flooding may broadly be divided into four phases. The first phase, from mid September through to the end of the month, resulted in significant, but localised, urban flooding. The second phase was concentrated in southeast England as a result of the extraordinarily wet period from 9-12th October. The third phase, during which there was extensive floodplain inundation across much of the UK, was triggered by very vigorous storms on the 29/30th October; heavy rainfall continued - generating further peak flows in early November - and high flows continued in many river systems well into December. The fourth phase was the result of unprecedented rises in water-tables in the Chalk and other aquifers. During December, groundwater-fed rivers in much of southern England experienced outstanding peak flows. Exceptional spring outflows and serious flooding, associated with extremely high water-tables, continued - in many areas - well into 2001.

The Environment Agency estimated that during the autumn of 2000, 10,000 properties were flooded at over 700 locations in England and Wales[2]. Serious flooding also occurred in Northern Ireland and southern Scotland. There was widespread dislocation of rail and road travel, and the prolonged saturation of agricultural land greatly restricted farming activities. Significant soil erosion was also reported[3]. The flooding focussed public, political and media attention on the possible effects of climate change on flood magnitude and frequency, the dangers of inappropriate floodplain development and, more locally, the contribution of land management practices to flood risk.

Antecedent Conditions and Soil Moisture Deficits

Overture to the flooding

Rainfall was well above average during the December 1999-February 2000 period across most of Scotland, northwest England and Northern Ireland. A wet spring ensured that soils were slow to dry out. High river flows were common during March and April 2000, and seasonal recessions in river flows began unusually late. Groundwater levels remained mostly above average - the wet spring having prolonged the aquifer recharge season. Baseflow contributions to many spring-fed streams were high, and recessions did not begin until June in many eastern and southern catchments. Summer (June-August) rainfall totals were appreciably below average, and there was a typically brisk decline in flows in rivers draining impervious catchments. However, flows in most groundwater-fed rivers continued at healthy rates through the summer. The River Test (in Hampshire), for example, recorded its highest August mean flow for 30 years - despite below average catchment rainfall for the summer. With limited capacity to accommodate further surface runoff, spring-fed rivers were particularly vulnerable to intense summer storms.

Soil moisture deficits

Throughout most of the UK, dry soil conditions during the summer substantially moderate the risk of flooding in most years. This is particularly true of the English Lowlands where significant soil moisture deficits (SMDs) - which provide an indicator of the dryness of soil profiles - are normally maintained through much of the autumn. Soil moisture conditions during 2000 departed considerably from the normal pattern.

The variation in soil moisture deficits during 2000 are shown in Figure 1 for six MORECS[14] (Met Office Rainfall and Evaporation Calculation Service) squares - see Figures 2 or 3 for the locations of the squares. The highest end-of-month SMD values generally occurred at the end of August 2000. In most western and northern areas, peak SMDs were below the long term late-summer average. By contrast, throughout most of southern and eastern England the summer ended with SMDs in excess of 100mm, in most areas a little higher than the late-August average.

In terms of vulnerability to flooding, September proved to be a pivotal month. It began with dry soils in the eastern lowlands but, from mid-month, soil profiles wetted up as bands of sustained frontal rainfall crossed the UK. A significant contributory factor to the early onset of the autumn-winter 2000/01 flooding was the rapidity with which lowland SMD values fell during the early autumn in many catchments. Away from the South West, most western and northern catchments were close to saturation by late September. This is not an unusual circumstance, but to the east - where on occasions modest deficits are carried over into the following year - the pace of decline has few recent parallels. Soils continued to wet-up rapidly in early October and, by month-end, residual deficits were confined to a few areas adjacent to the Wash. The distribution of computed SMD values across Great Britain at the end of August and the end of October 2000 are shown in Figures 2 and 3. The change over the nine-week period is dramatic, and especially significant

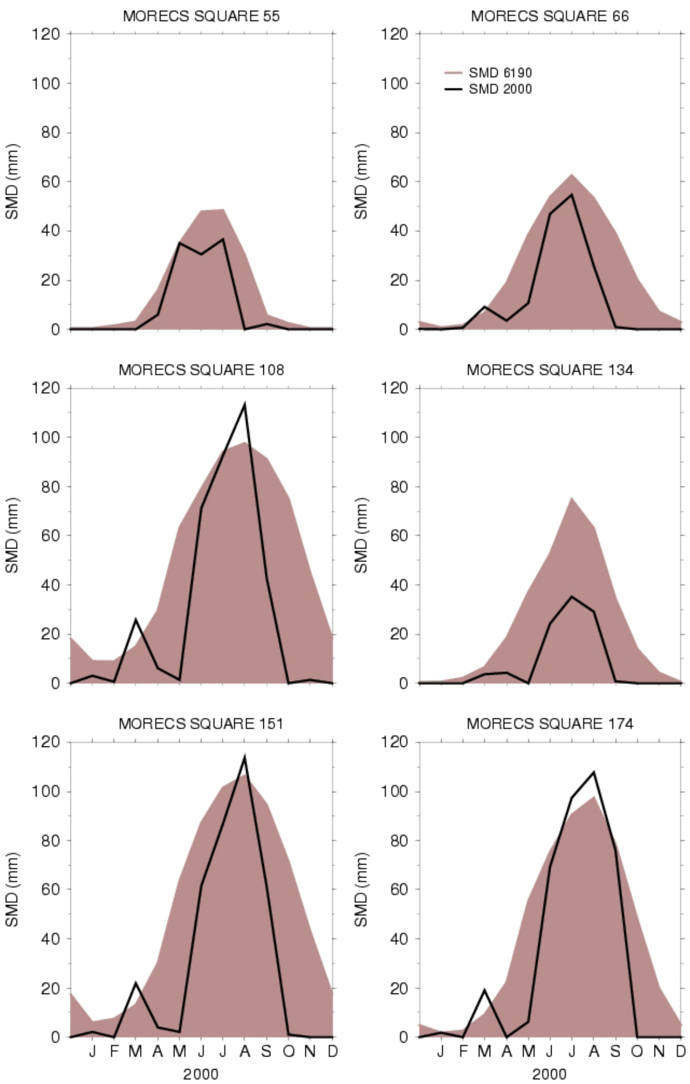


Figure 1 *Variation of end-of-month SMDs for six MORECS squares across Great Britain.*

Note: SMDs are calculated for a grass cover.

Data source: UK Met Office.

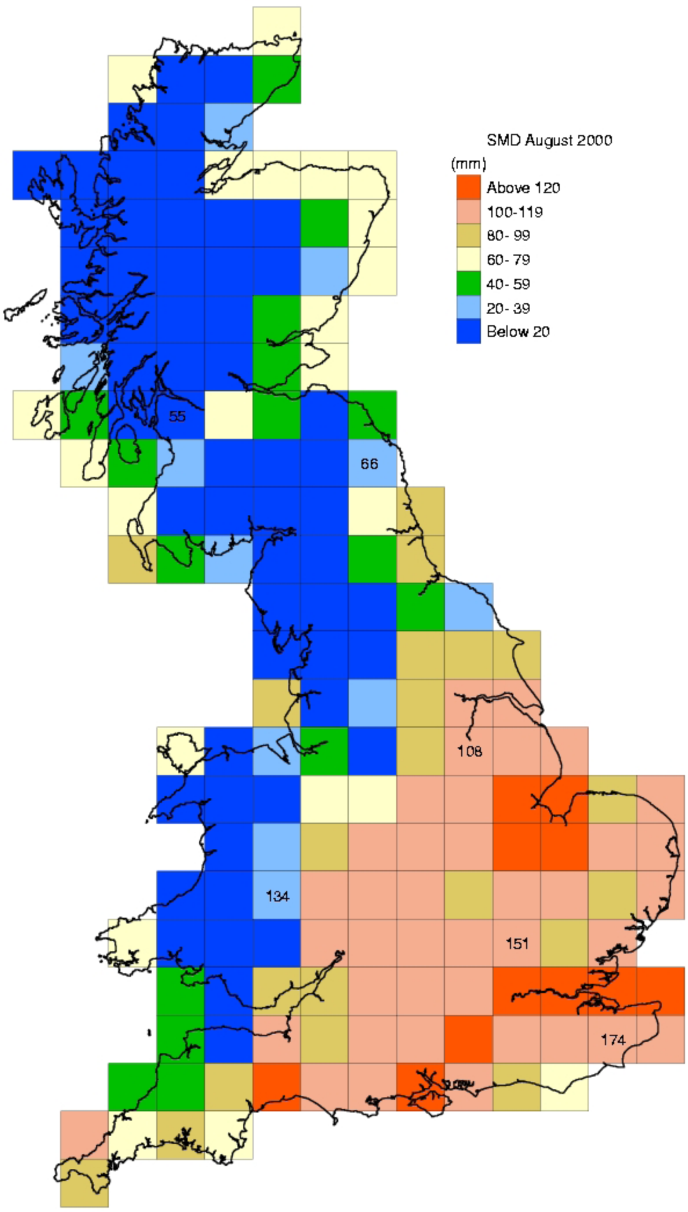


Figure 2 *SMDs across Great Britain at end of August 2000.*

Note: SMDs are calculated for a grass cover.

Data source: UK Met Office.

in parts of eastern England where soils approached saturation around two months earlier than the average for the preceding 10 years. Rapid eliminations of lowland SMDs have occurred before, most recently in 1998 and 1987, but in 2000 many catchments registered their largest August-October decline in the 40-year MORECS series. In a typical year, the modest water content of lowland soils in late October provides the capacity to absorb significant additional rainfall and delay the seasonal recovery in river flows (and groundwater levels) by a further 4-8 weeks. In 2000, the saturated nature of most catchments made them very vulnerable to further rainfall from early October.

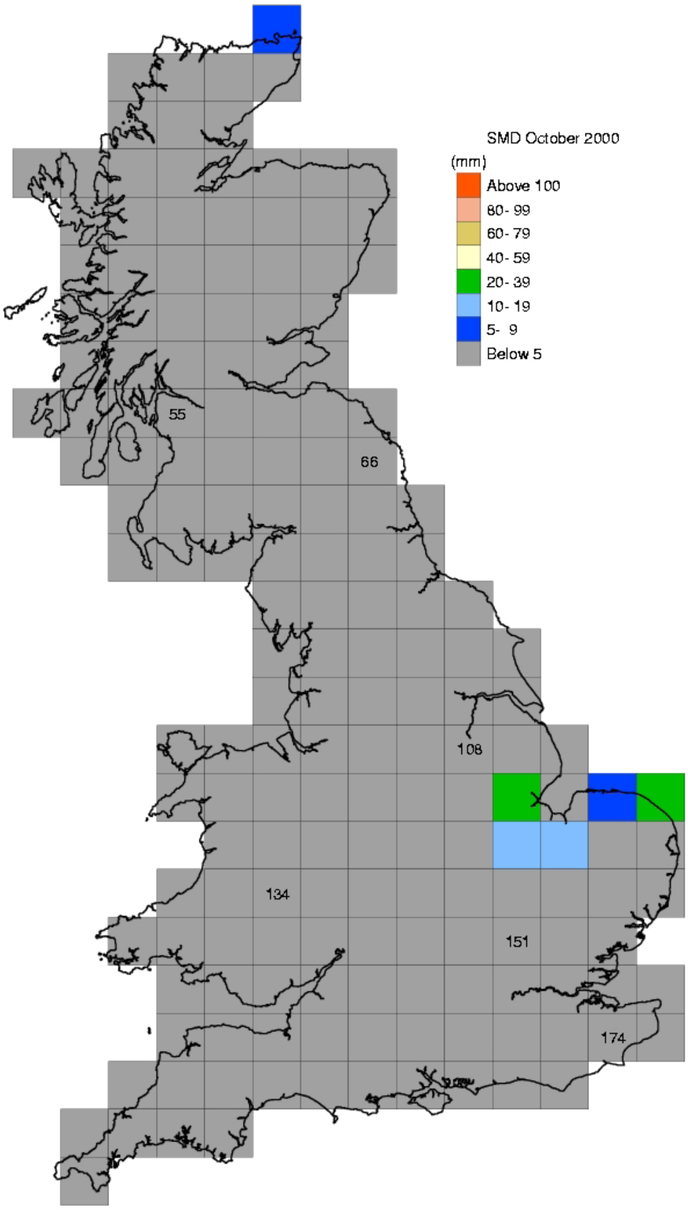


Figure 3 *SMDs across Great Britain at end of October 2000.*

Note: SMDs are calculated for a grass cover.

Data source: UK Met Office.

The Sequence of Major Flood Episodes

In common with most protracted flood episodes, the 2000/01 floods was characterised by large spatial and temporal variations in severity, but four reasonably distinct phases could be identified:

First phase: Localised heavy rainfall from mid September onwards

Intense rainfall was reported from many localities in across southern Britain at the end of the second week of September - causing local, mostly urban, flooding in (amongst other areas) Portsmouth, parts of west London, Penzance and West Sussex. On the 19th, large areas of the Midlands and East of England reported more than 20mm of rainfall. The 28/29th September period was also very wet, notably in northern parts of the UK, and flooding was reported in Bangor (Northern Ireland).

Second phase: Concentrated in south-east England during and after the extraordinarily wet period of 9-12th October

The worst hit areas were southwest Kent and East Sussex, where a near-stationary front (with embedded thunder calls) was responsible for exceptional rainfall. Barcombe recorded 175mm in less than 72 hours (return period approx. 400 years). Rivers draining impermeable catchments in Kent and Sussex (e.g. the Uck, Ouse and Teise) registered very high flows, with particularly severe flooding across parts of the catchments of the Medway and Sussex Ouse. In Lewes, the Environment Agency estimated that on 12th and 13th October 817 properties and business were flooded and needed to be evacuated[4]. Flooding also occurred across southwest England, in parts of Northern Ireland and in Dumfries and Galloway in Scotland.

Third phase: Widespread inundation of floodplains across much of the UK

There was persistent rainfall across many catchments on the 29/30th October, with many areas reporting falls of greater than 40mm. Persistent rainfall continued through the first week of November, generating notably high flows (over the 5-8th November) in catchments across much of the country. The areas most severely affected were the South-East, Yorkshire, western catchments (especially the Severn Basin), parts of northern Britain and Northern Ireland. On 9th November, the Environment Agency reported that the area of land under floodwater around Selby on the lower Yorkshire Ouse was "bigger than Lake Windermere"[5]. Return periods in the 15-30 year range were ascribed to peak flows for many rivers in England and Wales, and maximum recorded flows were exceeded in some catchments - for example, the Whiteadder (a tributary of the Tweed) and the Annacloy in Northern Ireland.

High flows continued in many river systems well into December but declined steeply in most impermeable catchments towards year-end.

Fourth phase: Groundwater flooding from December 2000 onwards into 2001

Caused by the remarkable rises in water tables levels in the chalk and other permeable aquifers. Records from the Environment Agency confirmed that the recharge in some eastern outcrops was the highest for the autumn in a series since 1920[6]. This resulted in exceptional outflows from high level springs and extensive groundwater flooding. In December significant peak flows were recorded on the Avon and Itchen in Hampshire and the Lavant in West Sussex. Localised 'clear-water' flooding from springs, resulting from high water-tables, continued in many areas (e.g. the Berkshire Downs and Chilterns) well into spring 2001. Although drier than the preceding four months the January-April 2001 period was the wettest start to the year for England and Wales since 1951. Many catchments therefore remained saturated - and sensitive to further flooding - until the late spring of 2001. Many rivers and streams supported principally by groundwater remained above previous maximum flows for lengthy periods.

Rainfall

Synoptic conditions

A particular feature of the weather during autumn 2000 was the frequency of low-pressure systems - some notably intense - crossing the UK from the Atlantic. Most followed tracks further south than usual, a reflection of the unusual southerly position of the Polar Front. Exceptional sea surface temperature gradients over the North Atlantic (as occurred in late 2000) have been shown to be associated with the passage of vigorous frontal systems[7]. During the autumn, the paths of the most intense low pressure systems largely determined which catchments were most severely affected by the associated flooding.

Extensive rainfall generated by particularly vigorous frontal systems during October 2000 resulted in the second wettest October (after 1903) on record for England and Wales, and the highest monthly rainfall total since November 1970. Thunder cells embedded in a semi-stationary front caused especially heavy rainfall across parts of Kent and Sussex in mid October. Low pressure systems, commonly with notably low central pressures, continued to track across central and southern Britain, producing outstanding rainfall accumulations. However, the speed of some frontal systems was a moderating factor; their rapid passage across the country helped to reduce storm rainfall totals. There was no respite from frontal rainfall until well into December when, despite the final two weeks being relatively dry, regional monthly rainfall totals again comfortably exceeded the December average across most of the UK.

During January 2001, many parts of the UK recorded below average rainfall, but the weather across the South-East continued wet. Vigorous frontal systems tracked across the UK early in February and, with only modest evaporation demands typical of the late winter, most catchments remained close to saturation. Southern England was again very wet during March. However, regional variations were large - northern England, Scotland and Northern Ireland were comparatively dry during March. During April, low-pressure systems continued to track across central and southern Britain. For England and Wales, April 2001 ranked amongst the wettest half dozen since 1935. May 2001 was generally dry, ending the remarkable period of eight successive wet months across much of the English lowlands. The warmer, drier weather continued into June and finally brought to a close an extraordinarily prolonged wet episode - although the risk of localised summer flooding from intense convective storms remained.

Rainfall accumulations - national and regional

A distinctive feature of the weather during the autumn and winter of 2000 was that, in addition to intense storms which triggered almost immediate flooding, there were prolonged periods of rainfall across many catchments. The frequency of these wet interludes is reflected in the accumulated monthly rainfall totals for England and Wales over the September 2000 to April 2001 period. Figure 4 compares the progressive monthly rainfall accumulations from September 2000 to April 2001 with the corresponding maximum accumulated rainfall totals for the full England and Wales rainfall series (1766-1999). For each of the periods from November onwards (i.e. the September to November period, then September to December, etc.), the 2000/01 accumulated rainfall totals exceeded the previous maxima. The outstanding nature of the rainfall is emphasised in Table 1, which ranks the highest rainfall accumulations over four- and eight-month periods (starting in any month of the year) using the homogenised England and Wales rainfall series[1]. The 2000/01 totals rank as the highest over both the four- and eight-month periods. Largely as a result of the extraordinary autumn and early winter rainfall, record England and Wales rainfall totals were established for accumulations extending up to 14 months.

The regional distribution of accumulated rainfall across the UK during the period September to December 2000 is shown in Figure 5 and Table 2. Across all regions of England rainfall totals over that period exceeded 150%

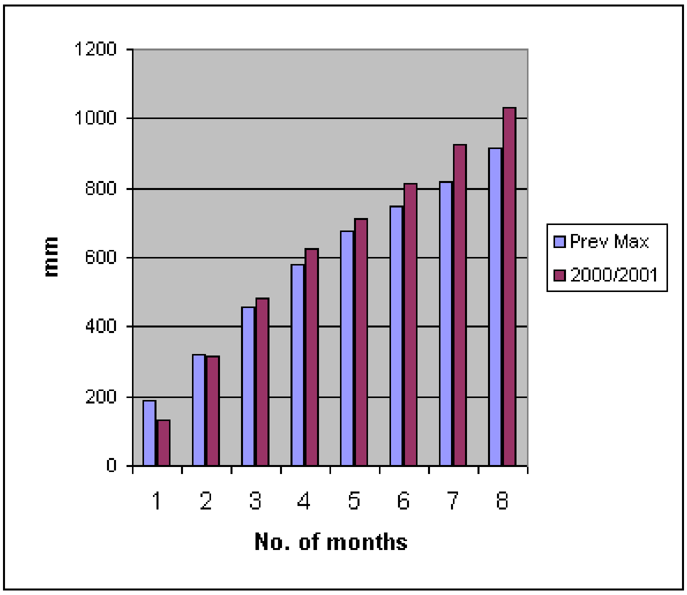
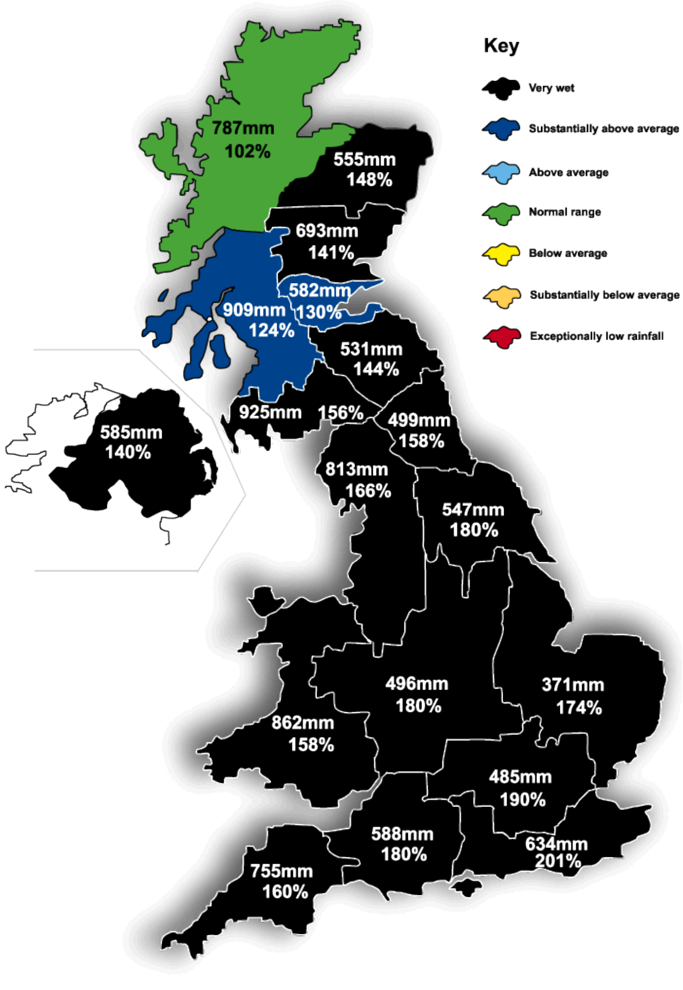


Figure 4 *Accumulated monthly rainfall totals for England and Wales from September 2000.*

Data source: CRU/Hadley Centre homogenised England and Wales rainfall series (from 1766).

of the 1961-90 average. Values equal to or greater than 180% of the 1961-90 average indicate clearly the very significant rainfall recorded from Kent to Dorset, and northwards through the Thames, Severn and Trent basins to Yorkshire. It was the wettest four-month period across the Thames catchment since records began in 1883. Rainfall over the September-December period also exceeded existing four-month maxima across most gauged catchments in England and Wales; testimony to the singular nature of the late-2000 rainfall (but note, relatively few gauged catchments have areal rainfall records extending back more than 40 years).



The rainfall figures are provisional for all regions

Figure 5 *Regional rainfall for the UK, September to December 2000.*

Note: percentages relate to the 1961-90 average.

Data source: UK Met Office

The rainfall gradient across Great Britain, evident from Figure 5, is of particular interest. Regions along a southeast-northwest line received the following percentages of the 1961-90 average rainfall for September to December 2000 (actual totals in brackets):

Southern	201%	(634mm)
Midlands (Severn-Trent)	180%	(496mm)
Solway	156%	(531mm)
Highland	102%	(787mm)

This shows a significant moderation in the normally much more pronounced 'drier south-east to wetter north-west' rainfall gradient. It reflects the tendency of rain-bearing weather systems from the Atlantic to take more southerly routes than usual during the autumn and early winter of 2000.

Table 1 *Wettest n-month periods for England and Wales.*

Note: the % of long term averages (LTA) relate to the n-month periods which end with the month listed in the next column.

Data sources: CRU/Hadley Centre England and Wales rainfall series (from 1766).

Rank	4-month (mm)	% of LTA	End of Period (mm/yyyy)	8-month (mm)	% of LTA	End of Period (mm/yyyy)
1	640	178	12/2000	1033	166	04/2001
2	624	175	01/1939	1014	152	01/1853
3	599	176	10/1799	988	148	02/1961
4	591	167	11/1852	946	142	01/1873
5	563	158	01/1961	941	141	01/1769
6	548	161	10/1903	915	137	01/1840
7	546	161	10/1775	913	147	04/1877
8	538	151	01/1873	908	136	01/1928
9	534	164	02/1915	902	135	02/1904
10	527	162	02/1877	901	135	02/1883

Table 2 *Rainfall accumulations and return period estimates, September to December 2000.*

Data sources: UK Met Office and CRU/Hadley Centre (see below).

Area	September to December rainfall			Return period estimate (years)
	2000 (mm)	1961-90 avg	% of 1961-90 avg	
England & Wales	640	353	181	>> 200
North West	813	490	166	> 200
Northumbrian	499	316	158	60-90
Severn Trent	496	276	180	>> 200
Yorkshire	547	304	180	>> 200
Anglian	371	213	174	> 200
Thames	485	256	190	>> 200
Southern	634	316	201	>> 200
Wessex	588	327	180	> 200
South West	755	473	160	50-80
Welsh	862	547	158	60-90
Scotland	723	600	121	5-10
Highland	787	769	102	2-5
North East	555	376	148	50-80
Tay	693	492	141	20-30
Forth	582	447	130	10-15
Tweed	531	370	144	30-40
Solway	925	592	156	110-150
Clyde	909	731	124	5-10
Northern Ireland	585	418	140	15-25

Note: All rainfall totals are provisional. The figures for England & Wales are derived by the Hadley Centre and are updates of the homogenised series developed by the Climate Research Unit; the other national and regional figures are provided by the Met Office (and are derived from different raingauge networks to those used to derive the CRU data series). The return period estimates are based on tables provided by the Meteorological Office (see Tabony, R.C., 1977, The variability of long duration rainfall over Great Britain, Scientific Paper No. 37) and relate to the specified span of months only (return periods may be up to an order of magnitude less if n-month periods beginning in any month are considered); RP estimates for Northern Ireland are based on the tables for north-west England. The tables reflect rainfall over the period 1911-70 and assume a stable climate. Artifacts, in the Scottish rainfall series in particular, can exaggerate the relative wetness of the recent past.

Patterns of daily rainfall

There were comparatively few dry spells across many parts of the UK during the period from September to December 2000 but the frequency of thunderstorms (often associated with frontal systems) resulted in large spatial variations in rainfall amounts. Many areas recorded notable rainfalls across a range of timespans during the autumn-winter 2000/01 period. From the 9-12th October Barcombe (East Sussex) recorded 175mm in less than 72 hours (return period: approx. 400 years) and West Freugh (near Stranraer in Dumfries and Galloway) received 125mm in 48 hours. Over the 29/30th October Andover (Hampshire) recorded 62.2mm in 16 hours. Linton-on-Ouse (North Yorkshire) reported 154.8mm over the 10 days beginning 29th October. In Northern Ireland, 167mm was recorded in a 48-hour period during 5-7th November at Silent Valley.

Figure 6 provides a guide to the pattern of rainfall over the September-December period; it shows daily totals for Barcombe, beside the Sussex Ouse, and Scar House in the Pennines. The former experienced a number of very significant short duration rainfall events as well as notable n-day accumulations. Daily totals of around 26mm or more may be expected in this area, on average, once every 7-10 months. However, no less than eight daily totals reached this threshold over the September to December period; the most outstanding were 115mm on October 11th (> 450 year return period) and 46mm on October 29th (> 60 year return period). The four-month rainfall total of 970mm for September to December 2000 for the Barcombe raingauge was the equivalent of 120% of the annual average rainfall (832mm).

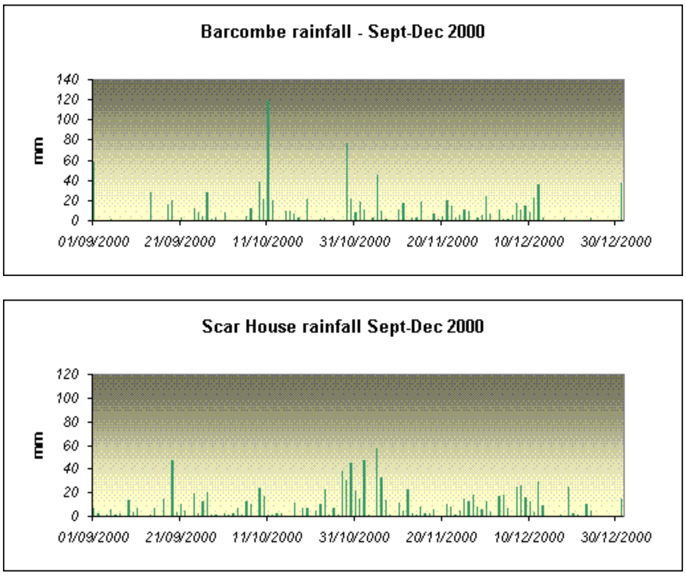


Figure 6 *Daily rainfall, September to December 2000 for Barcombe (Sussex) and Scar House (Yorkshire Pennines).*

Data source: Environment Agency.

At Scar House Reservoir (in the upper Nidd catchment) average annual rainfall is around 70% greater than at Barcombe. Some similarities to the rainfall distribution in the South-East can be recognised, but a substantially higher proportion of the autumn rainfall was concentrated into a remarkably wet episode across the Pennines, beginning in late October. Over the six days up to and including November 2nd, rainfall totalled 196mm (RP approx. 60 years) and the 11-day total reached 300mm (RP approx. 250 years). These exceptional accumulations resulted from sustained rainfall associated with the passage of low pressure systems rather than short, intense storm events.

River Flows

The geographical spread of high flows and flooding

Flooding was experienced in most regions across the UK at some time or another during the autumn and early winter of 2000. Gauging stations recording notable peak flows during the September to December period showed a very wide distribution, from Northern Ireland and south-west Scotland to Devon and Kent. Flows at most river gauging stations greatly exceeded the long-term averages for extended periods. Spates were frequent and high flows were maintained for lengthy periods. An impression of the geographical extent of the flooding during September to December 2000 can be gained from daily flow hydrographs for the year 2000 which are featured in the Hydrological Review of 2000; the shaded sections at the top and bottom of the hydrographs indicate the extreme daily flow envelope based on data up to and including 1999.

In many rivers, primarily those fed by groundwater, high flows continued through the winter and into the spring of 2001. Daily mean flow hydrographs for 2001 for six rivers which carried high flows early in the year are shown in Figure 7. During the first four months of 2001, daily flows in the Mimram and Ewelme Brook - both draining from the Chalk - exceeded pre-2000 maxima for lengthy periods; the Itchen also recorded daily mean flows considerably higher than any previously recorded. Flows in the Thames - which drains a catchment of mixed geology - exhibited less extreme behaviour, but daily mean flow values remained high.

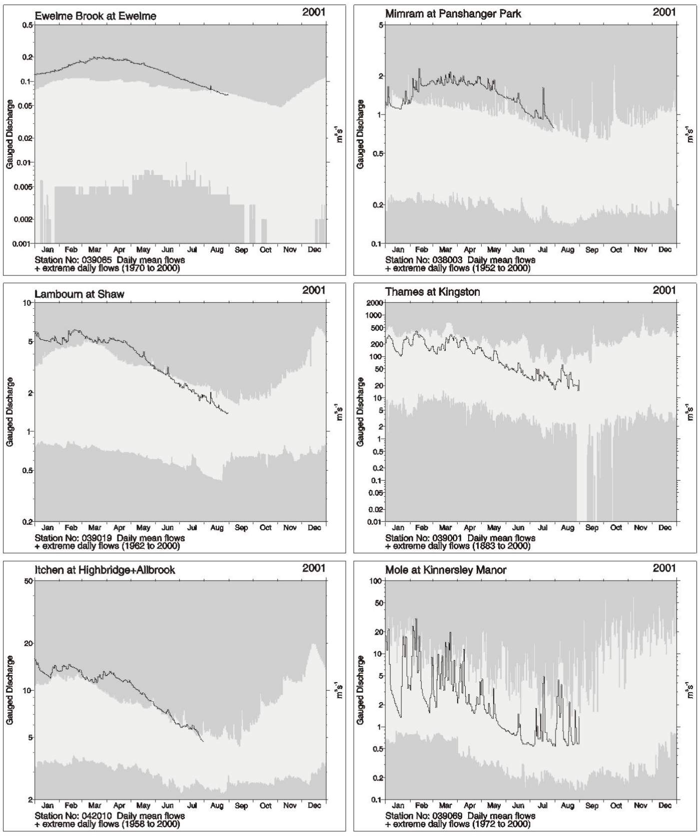


Figure 7 *Daily mean flow hydrographs for 2001.*

Note: dark shading indicates the maximum and minimum daily flows for the pre-2000 period. Some 2001 flows are provisional.

Data source: Environment Agency.

Distribution of 'Severe Flood Warnings'

During September 2000, the Environment Agency (EA) introduced a new three-level Flood Warning system across England and Wales. The most serious, the 'Severe Flood Warning' (SFW), indicated 'Imminent danger to life and property'. Throughout the period of severe flood risk, the Agency listed daily on its national Website (http://www.environment-agency.gov.uk/) details of the SFWs that were currently in force. The number and geographical spread of SFWs in force across England and Wales at any one time provide a guide to the extent of the most serious flooding, at least in river systems where people or property are at risk. In the report 'Lessons Learned'[2] the Agency noted that 1,437 flood warnings (at all three levels) had been delivered over the period of serious flooding, of which 190 were SFWs. The 190 SFWs were distributed across the Agency's regions as follows:

Anglian	9
Midlands	36
North East	53
North West	3
Southern	50
South West	15
Thames	9
Wales	15

On 6th November 2000, SFWs were in force on around 40 rivers, large and small, across England and Wales. These ranged from the Medway, Ouse and Uck in Kent and Sussex - which had first flooded in mid October - to the Welsh Dee, Monnow and Severn (from the Welsh border right down to Gloucester). Across the Midlands SFWs applied on the Trent, Derbyshire Derwent and Churnet, and in Yorkshire on the Aire, Derwent and Ouse. Elsewhere, they were in force on the Gaunless and Wear in the North-East, and the Axe and Dorset Frome in the South-West.

Environment Agency Flood Warnings were issued for areas where there were perceived flooding risks to people and property. However, high flows were also carried along river reaches elsewhere without such risks - either because flows could be safely contained within channels, or because designated flood plains and washlands could accommodate out-of-bank flows.

Severity of the flooding

Peak river flows provide an important but incomplete guide to flood severity. This is particularly true for protracted flood episodes when the duration and frequency of exceptional flows are influential in determining the overall impact of the flooding.

In this section the hydrological severity of the flood flows is considered across a range of timeframes and spatial scales.

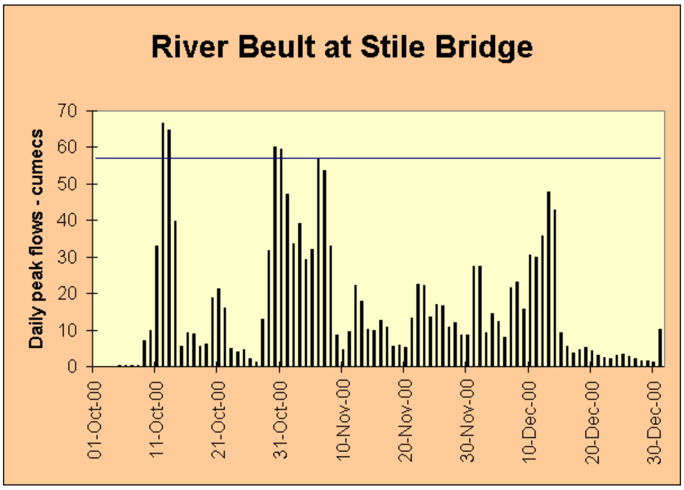
Peak flows

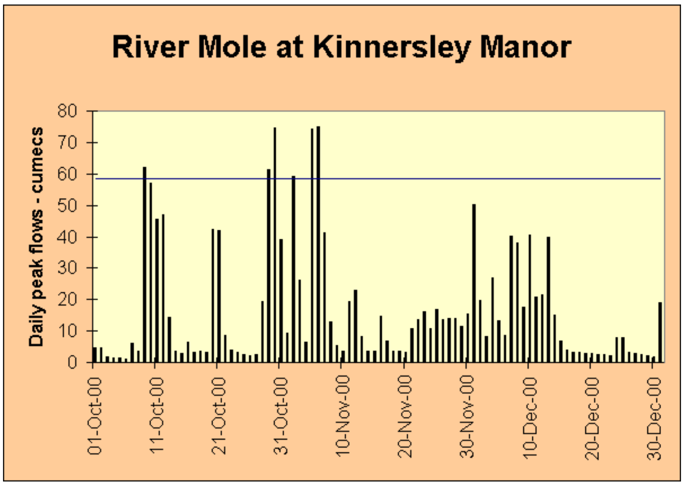
The 2000/01 floods were more remarkable for the geographical spread of the catchments affected than for the peak flows recorded. Nonetheless, many outstanding maximum flows were registered, and the range of recorded flows was extended over wide areas. Table 3 lists individual peak flow values for a representative selection of rivers across the UK which experienced major flood events during the autumn and winter of 2000/01. These include many - but not all - sites which experienced the most extreme flood flows. An associated return period range accompanies each flow value. These rarity estimates were calculated using the methodology presented in the Flood Estimation Handbook[8]. Some return periods have been based on provisional peak flow data; correspondingly they are subject to future revision. In broad terms, the most extreme floods from a hydrological perspective were the October events in responsive catchments in Sussex and Kent, and the winter peak flows in a number of Chalk streams and rivers.

Sequences of high flows

An important feature of the autumn-winter 2000/01 flooding was that in many rivers sequences of separate, but significant, high flow peaks were recorded; multiple events were particularly common in the South East. The combination of saturated catchments, a vigorous westerly airflow and (from early October) limited additional channel capacity to accommodate further runoff, implies a clear vulnerability to multiple flood events. Similar circumstances have occurred before (for example, in the winters of 1989/90 and 1994/95), but preliminary examinations of representative flow records reveal no close similarities to the frequency of bankfull, or higher, flows during 2000/01 across much of the English Lowlands - the South-East particularly.

Figure 8 shows time series plots of daily maximum flows at gauging stations on the Beult, Mole and Wharfe for the period October to December 2000. Five-year return period flows (for the period up to and including 1999) are indicated. For the two southern rivers, Weald Clay predominates in the catchments above the gauging stations. The Wharfe at Flint Mill has a larger catchment area (760km^2) with geology of Carboniferous Limestones, grits and Coal Measures, running up onto Pennine moorland. Comparing the three hydrographs in Figure 8, there were three major high flow events in both the Beult and Mole between 8th October and 10th November 2000. The Kentish village of Yalding, close to the confluences of the Beult and Teise rivers and the Medway, experienced a renewed bout of flooding as each of these three flow peaks passed[4]. Through the rest of November and into





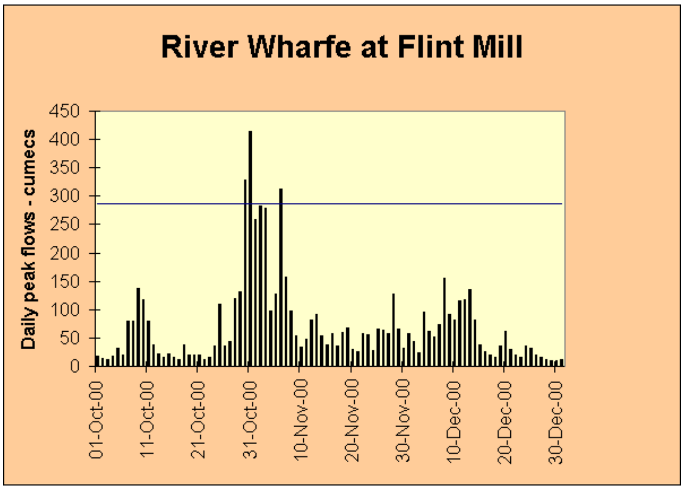


Figure 8 *Daily maximum flow hydrographs, October to December 2000.*

Note: the five-year return period threshold is indicated on each plot. Some daily peak flows are provisional.

Data source: Environment Agency.

Table 3 *Peak flows and associated return periods for the 2000/01 flood episode.*

Note: Many of the peak flows are estimates and are subject to future revision.

Data sources: Environment Agency, Scottish Environment Protection Agency and the Rivers Agency (Northern Ireland).

NRFA Station Number	River	Station	Date	Peak Flow (cumecs)	Estimated Return period (years)
Scotland					
20003	Tyne	Spilmersford	06-Nov-00	93	15 - 20
21022	Whiteadder Water	Hutton Castle	07-Nov-00	285	20 - 25
81002	Cree	Newton Stewart	25-Oct-00	370	20 - 30
EA Northeast					
25005	Leven	Leven Bridge	02-Nov-00	125	50 - 60
27002	Wharfe	Flint Mill Weir	31-Oct-00	415	20 - 35
27041	Derwent	Buttercrambe	09-Nov-00	172	60 - 80
EA Midlands					
28009	Trent	Colwick	08-Nov-00	1019	50 - 60
54001	Severn[1]	Bewdley	02-Nov-00	556	20 - 30
54040	Meese	Tibberton	06-Nov-00	9.6	40 - 50
EA Anglian					
37005	Colne	Lexden	31-Oct-00	21	10 - 15
EA Thames					
38003	Mimram[2]	Pansanger Park	24-Mar-01	1.97	> 150
39001	Thames[3]	Kingston	07-Nov-00	440	10
39019	Lambourn[2]	Shaw	23-Feb-01	6.14	80 - 120
39020	Coln	Bibury	14-Dec-00	7	25 - 50
39069	Mole	Kinnersley Manor	06-Nov-00	75	15 - 20
39065	Ewelme Brook[3]	Ewelme	27-Mar-01	0.202	100 - 150
EA Southern					
40003	Medway	E Farleigh/Teston	13-Oct-00	274	30 - 60
41006	Uck	Isfield	12-Oct-00	113	80 - 120
42010	Itchen	Highbridge & Allbrook	12-Dec-00	22	> 150
EA Southwest					
50001	Taw	Umberleigh	30-Oct-00	618	70 - 100
52005	Tone	Bishops Hull	30-Oct-00	123	20 - 30
EA Welsh					
62001	Teifi	Glan Teifi	30-Oct-00	310	5 - 10
67015	Dee	Manley Hall	30-Oct-00	467	30 - 50
Northern Ireland					
205011	Annacloy	Kilmore Bridge	07-Nov-00	62	15 - 30
205020	Enler	Comber	08-Dec-00	60	> 50

Notes:
1. The peak water level on the Severn at Bewdley on 2 November 2000 was third highest in a series from 1921.
2. Return periods for the Mimram and Lambourn are based on 5-day maxima.
3. The peak values for the Thames and the Ewelme Brook are based on annual maximum daily mean flow values.

Best estimates of return period ranges have been made using pooled or single-site distributions (as appropriate), based on the methodology used in the Flood Estimation Handbook (Institute of Hydrology, 1999). A proportion of the return period estimates have been based on provisional data peak flow assessments; the RPs as listed should be regarded as indications of the scale of the flood flow event, rather than as definitive values.

December, runoff responses from the near-saturated clay catchments of the Beult and Mole reflected the continuing rainy weather. The frequency of notably high daily mean flows for the Mole emphasises the singular nature of the 2000/01 flood episode. During October 2000 to February 2001, a threshold value of 20 cumecs was exceeded on 21 days. This is nearly twice the previous record of exceedence (11 days) during October 1997 to January 1988 in a series from 1974.

In contrast with the three major flow peaks during October and November in the Beult and Mole, peak flows in the Wharfe were concentrated into an eight day period from 30th October. Daily mean flows exceeded 150 cumecs at Flint Mill weir for five consecutive days - an unprecedented occurrence in a 45 year flow record. High flows in both the Mole and Wharfe during February 2001 show that these catchments - as for most throughout England and Wales - remained close to saturation, despite drier weather during December and January.

Flow accumulations over long periods

To provide a broad framework within which to assess the rarity of the autumn-winter 2000/01 floods, an England and Wales daily outflow series for the period 1940-2000 was developed. It is based on daily flow data for five major rivers (Thames, Severn, Trent, Dee and Wharfe) - some modelling was involved to assess the earliest flows for the Trent and Wharfe. The exceptional duration of high river flows during the autumn and early winter of 2000 can be demonstrated by examining average flows over different periods of days for periods of notably high runoff. Table 4 ranks 10-, 30-, 60-, and 90-day maximum flows for the England and Wales outflow series was well as for the Trent, Thames, Severn and Welsh Dee. At the national scale the 1947 flood event is pre-eminent over the shorter timespans but the rankings confirm the exceptional nature of the late-2000 high flows over the longer durations.

Within individual river basins, the relative severity of the October-December 2000 high flows similarly tends to increase for the longer durations. The rankings in Table 4 also reflect differences in runoff patterns in late 2000 and the available length of flow record for each featured river. The Trent has the shortest flow record (42 years) and is the only one for which 1947 flows are not available (estimates of the peak in 1947[9] indicate that it exceeded the 2000 maximum by a modest amount). Correspondingly, the n-day accumulations for 2000 eclipse, or closely approach, the previous maxima for all four n-day periods listed. For the Thames, Severn and Welsh Dee the significance of the 2000 flows increases as the timeframe is extended - they rank amongst the highest on record for the 90-day period.

The significance of the protracted spate conditions across the full compass of the 2000/01 flood episode is underlined by the winter half-year (October-March) runoff totals for gauging stations throughout the country. Initial analyses suggest that around three-quarters of the 800 primary gauging stations in England and Wales exceeded their previously recorded maximum winter half-year (October to March) runoff totals, some by very wide margins. Further confirmation is provided by the number of days for which flows exceeded the 97%ile threshold during the autumn, winter and early spring of 2000/01. On average the 97%ile flow is exceeded for about 10 days a year but for 2000/01 higher flows on the Thames were recorded on 86 days. Such a period of sustained (but not continuous) exceedence is at least four weeks longer than for any other high flow episode in the 118-year flow series.

Historical Perspective

Even the most extreme individual events during the 2000/01 flooding do not compare with the most damaging localised fluvial floods of the twentieth century, such as at Lynmouth in August 1952[10] and Louth in May 1920[11]. More damaging flooding has occurred at regional levels, as across southern England in 1968, in Scotland in the winter of 1993/94 and from South Wales to the Wash around Easter 1998[12]. However, when considered at the national scale, the 2000 flooding was remarkable in its extent and duration - as such it is without any close modern parallel.

Comparisons with previous protracted flood events are hampered by the fact that each major flood episode has a unique spatial and temporal signature. However, a daily outflow series for England and Wales (based on flows in five major rivers) allows broad comparisons to be made, and a selection of six major flood events from this series (covering the last 60 years) appears in Figure 9. In terms of maximum flows, the flood of March 1947 is clearly outstanding[9]. This was very different in character to the autumn-winter 2000/01 flooding, and almost all other protracted flood events since 1947. It was a snowmelt-generated event which produced very high runoff rates over still-frozen ground. However, the duration of high flows around the 1947 event was in general shorter than during later extensive flood episodes (see Table 4).

Unlike the 1947 event, the other flood episodes shown in Figure 9 were not grouped around a single concentration of extreme flows. In early December 1960, the peak for the England and Wales outflow series came after a sequence of sustained high flows which had started in October. Although there was also a peak towards the end of January 1995 in the December 1994-February 1995 episode, that peak was as no means as pronounced as in December 1960. The December 1976-February 1977 flood episode also indicates a pattern of higher flows later in the period, but in December 1965-February 1996 the higher flows came earlier in the period of flooding. On timing within the calendar year, the 2000/01 floods reached very high flows early in the autumn, although there were also significant flows in late October and early November of 1960. The floods in 1965/6, 1976/7 and 1994/5 were winter flooding episodes.

A defining feature of the 2000/01 flood episode was the magnitude of the runoff over timespans of two

Table 4 *Ranked n-day maximum outflows for England and Wales* and four major river basins.*

Data sources: National River Flow Archive/measuring authorities.

Gauging station	Rank	Flow	End mm/yy	Flow	End mm/yy	Flow	End mm/yy	Flow	End mm/yy
England & Wales' series 1940-2000	1	2094	03/47	1279	04/47	1027	12/00	809	12/00
	2	1593	11/00	1108	11/00	857	12/60	770	01/61
	3	1346	02/60	1008	12/65	823	05/47	717	03/95
	4	1270	12/60	958	12/60	813	02/95	700	02/66
	5	1221	02/95	945	03/77	793	02/94	682	03/94
	6	1188	12/65	940	02/95	748	03/77	645	04/47
	7	1146	12/54	924	02/90	744	12/54	641	01/55
	8	1136	03/77	909	01/94	734	01/66	641	03/90
	9	1130	02/46	891	12/54	705	02/90	634	03/77
	10	1116	01/82	893	12/46	685	01/47	598	04/51
River Trent at Colnwick 1958-2000	1	529	11/00	381	03/77	313	12/00	252	02/66
	2	517	02/60	362	01/66	277	03/77	251	12/00
	3	513	02/77	360	11/00	262	01/66	228	03/77
	4	438	12/65	357	12/65	250	12/60	221	01/61
	5	408	01/82	292	01/94	242	02/95	212	03/95
	6	396	01/95	288	02/95	241	02/94	207	03/94
	7	395	02/84	270	12/60	226	12/65	188	03/99
	8	370	02/76	269	02/60	219	02/84	186	03/88
River Thames at Kingston 1883-2000	1	633	03/47	425	04/47	300	02/28	267	03/15
	2	499	01/15	341	02/04	296	01/30	262	04/37
	3	465	12/29	340	01/15	295	03/37	256	02/30
	4	422	02/00+	337	01/30	295	02/15	256	12/00
	5	418	01/25	330	01/28	284	12/00	255	02/15
	6	406	03/33	303	03/37	279	05/47	255	01/61
	7	404	02/04	301	12/00	272	12/60	252	02/28
	8	403	11/74	297	01/25	272	03/28	227	04/51
River Severn at Bewdley 1921-2000	1	540	03/47	322	04/47	255	01/30	219	02/30
	2	423	02/46	310	12/65	251	12/00	203	12/00
	3	406	11/00	274	11/00	213	12/54	183	03/95
	4	388	12/65	272	12/79	210	01/66	183	02/66
	5	383	02/60	261	02/90	206	02/95	178	03/90
	6	374	12/29	256`	01/39	206	12/60	177	01/61
	7	374	01/48	253	01/94	205	02/28	176	01/55
	8	372	01/25	248	02/28	203	02/94	174	03/94
River Dee at Manley Hall (Erbistock) 1937-2000	1	226	03/47	135	04/47	121	12/00	98	12/00
	2	195	12/64	131	11/00	105	12/54	89	03/60
	3	192	11/00	118	12/60	101	02/60	88	12/54
	4	192	02/46	118	01/94	96	02/95	87	03/95
	5	177	12/59	114	11/54	94	02/94	81	02/83
	6	164	01/48	112	01/48	91	12/60	79	03/90
	7	160	12/54	110	12/65	90	02/48	79	01/61
	8	159	12/60	110	02/90	89	02/90	78	03/94

+ = 1900

** The index of England and Wales outflows is based on the combined daily flows of the Rivers Trent, Thames, Severn, Dee and Wharfe. Total outflow from England and Wales would be around seven times the figures given above.*

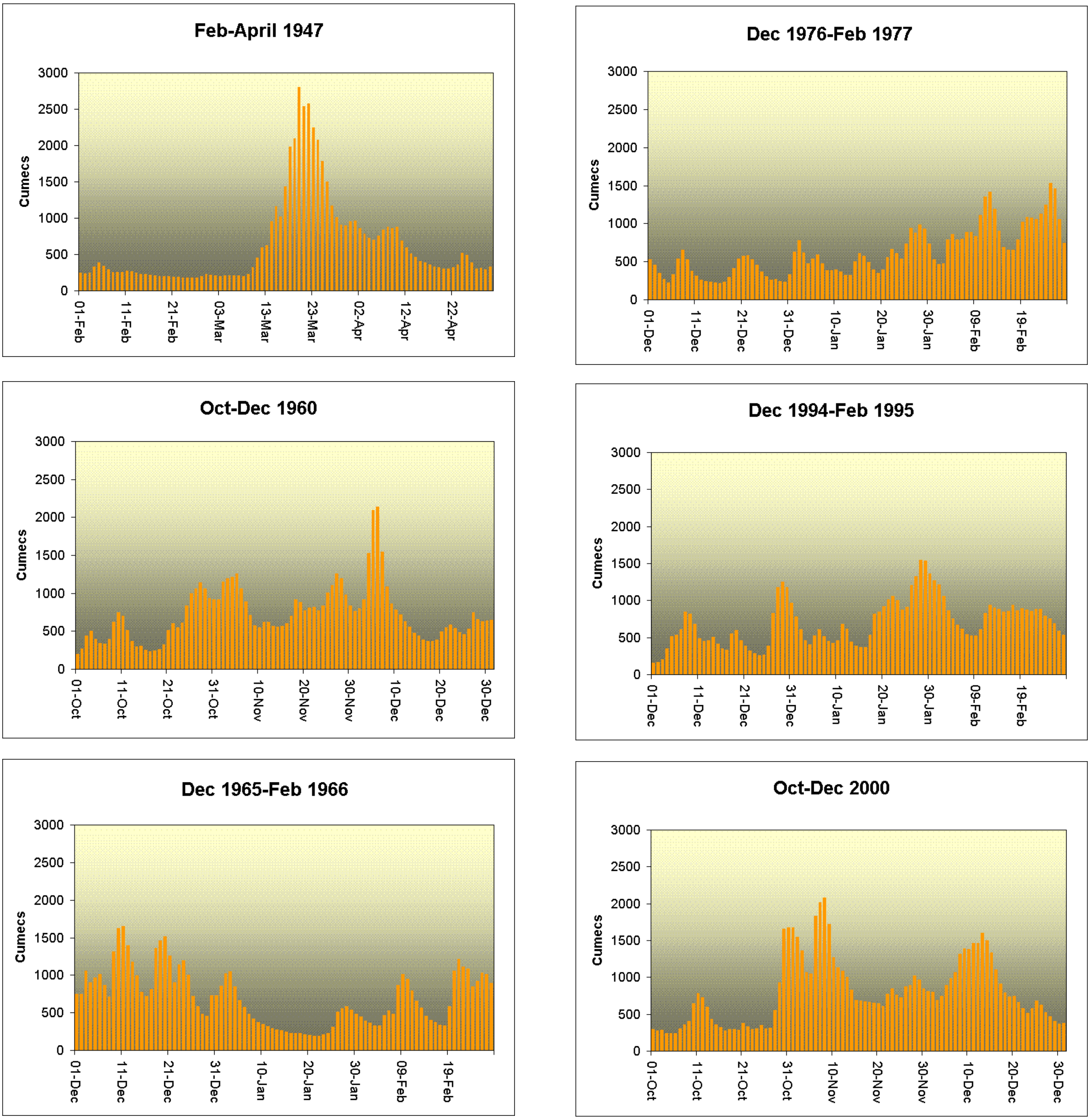


Figure 9 *A comparison of six major widespread flood episodes across England & Wales.*

Note: The hydrographs provide a guide to England and Wales outflows - based on the combined daily flows of the Rivers Trent, Thames, Severn, Dee and Wharfe (the total outflow from England and Wales would be around seven times the flow indicated on the individual plots).

Data source: Environment Agency.

to three months. The 90-day maximum during the September-December 2000 period exceeds all previous maxima in the 61-year England and Wales runoff series a series from 1940, and was around 25% greater than the maximum 90-day flow registered for the late winter and early spring of 1947.

The Groundwater Dimension

Over the winter of 2000/01 groundwater levels exceeded previous maxima over wide areas, springflows were remarkably high and protracted 'clear-water' flooding was experienced on a truly exceptional scale.

Rainfall, Effective Rainfall and groundwater recharge

For almost all major aquifer outcrop areas (see map for their locations) evaporative losses exceed rainfall throughout the summer. Groundwater replenishment (or recharge) is thus largely confined to the winter - extending through into the late spring in a few wet years. The dramatic decline in soil moisture deficits during the early autumn of 2000 heralded an exceptionally long recharge season. Throughout most of the autumn and winter of 2000/01 the preferred track of rain-bearing low pressure systems resulted in a rainfall distribution which greatly favoured the major aquifer outcrop areas in southern Britain. Large parts of the English Lowlands recorded rainfall totals between 60% and 80% above average for the recharge season; over the Thames catchment, the October 2000-April 2001 rainfall exceeded the previous maximum - in a series from 1883 - by a very substantial margin. Correspondingly, exceptional winter and spring rainfall was recorded over most of principal aquifer outcrop areas.

Assessments of Effective Rainfall (ER) provide an indication of how much of the rainfall over an aquifer outcrop actually contributes to the recharge of groundwater. ER estimates confirm that rates of aquifer replenishment during the autumn and winter of 2000/01 were extraordinary[6]. Across parts of the southern Chalk recharge during 6-8 weeks in the late autumn of 2000 exceeded the long term annual mean total[13]. Recharge rates declined in early 2001 but still remained well above average through into the late spring. Effective Rainfall over the winter half-year (October 2000 to March 2001) for selected areas in the Thames basin, are shown in Table 5; they indicate recharge amounts of between twice and three times the long term average. For comparison Table 5 also includes corresponding areal rainfall totals. The higher percentages associated with the Effective Rainfall relative to the actual rainfall reflect the non-linear relation between rainfall and aquifer recharge. In parts of eastern England a 50% increase in winter rainfall can more than double the amount of recharge.

Estimated percentage recharge in for 2000/01 in parts of southern and eastern England exceeded that for the Thames basin. Long term Effective Rainfall series - together with the outstanding rainfall totals over the 2000/01 recharge season across most major aquifer outcrop areas - suggest that, for the Chalk at least, there is no recorded precedent for the magnitude of groundwater replenishment experienced over the extended 2000/01 recharge season.

Table 5 *Winter (Oct-Mar) totals of rainfall and effective rainfall in the EA Thames Region, 2000/01.*

Data sources: Environment Agency (Thames Region Hydrological Summary).

Area	Rainfall (mm)			Effective Rainfall (mm)		
	Total	Long Term Average	% Long Term Average	Total	Long Term Average	% Long Term Average
West Area	562	360	156	428	223	192
South East Area	786	402	196	671	256	262
North East Area	646	331	195	513	172	298
Thames Region	661	368	180	534	222	241

Groundwater level variations and their effects

The 2000 recovery

The variation of groundwater levels during 2000/01- and for the preceding five years - is shown in Figure 10 for a representative set of observation wells and boreholes; some record gaps in 2001 are the consequence of Foot and Mouth restrictions. The shaded envelopes indicate the pre-1996 maximum monthly and minimum monthly levels. Exceptionally steep groundwater level recoveries characterise the last three months of 2000. Rapid recoveries of groundwater levels during the autumn and early winter have been a feature of several recent winters, for example in 1989/90 and 1997/98. However, in those cases recovery was from low, or very low, summer groundwater levels. In the autumn of 2000, by contrast, recoveries generally began with water levels in many aquifers around, or a little above, seasonal mean levels.

The subsequent rate of rise was remarkable; for half of the monitoring sites listed in Table 6 (see below), the overall rise equalled or exceeded twice the mean annual range. At West Woodyates (Dorset), the water level rose 25 metres in the 18 days to the 10th November. In the Carboniferous Limestone of Derbyshire, levels at Alstonfield registered an overall rise of more than 45 metres - unprecedented in a 30-year record. At Chilgrove (in the Chalk of West Sussex) the borehole began overflowing earlier in the year than at any time in a 165-year record; the borehole is thought to have overflowed only around half a dozen times since 1836. In the slower responding eastern Chalk outcrops and throughout much of the Permo-Triassic sandstones

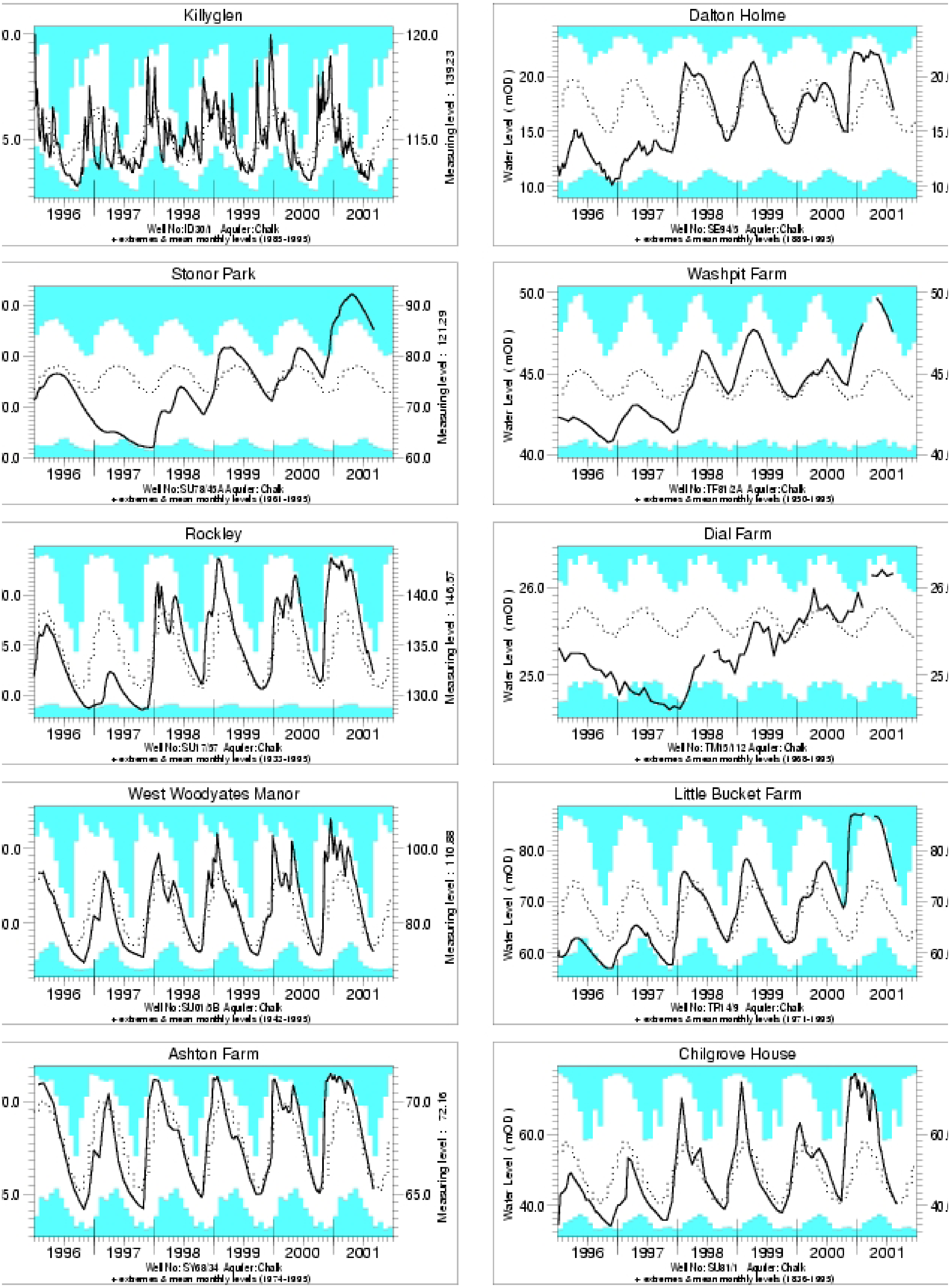


Figure 10 *Groundwater level hydrographs 1996 to 2001.*

Data source: National Groundwater Level Archive (British Geological Survey)/the Environment Agency.

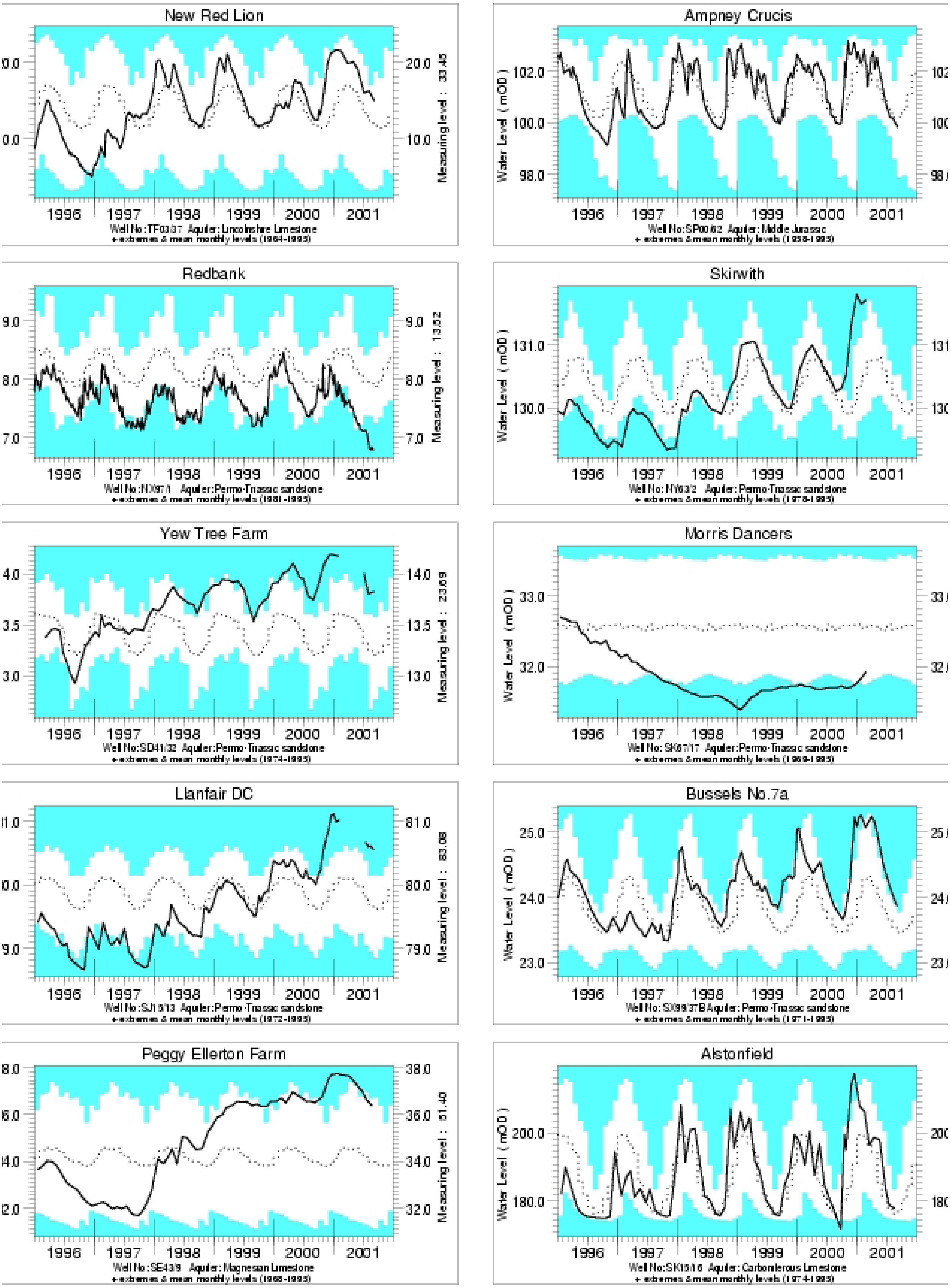


Figure 10 *(Contd.)*

Table 6 *Groundwater levels 2000/01 - seasonal rise and maximum levels.*

Note: m aOD = metres above Ordnance Datum.

Data sources: National Groundwater Level Archive (British Geological Survey)/the Environment Agency

Well site	National Grid Reference	Aquifer	First year	Mean annual range (m)	Rise - winter 2000/01 (m)	Max level pre-2000 (m aOD)	Max level 2000/02 (m aOD)
Wetwang	SE 958594	Chalk	1971	8.7	17.3	35.15	37.4
Redlands Hall	TL 452418	Chalk	1963	8.5	17.9	54.5	56.3
Compton	SU 776149	Chalk	1894	20.8	39.7	68.8	73.4
Stonor	SU 742892	Chalk	1961	7.5	19.8	87.4	92.1
Lime Kiln	ST 376067	Upper Greensand	1969	0.8	1.6	126.5	127.1
Llanfair DC	SJ 137556	Permo-Triassic sandstones	1972	0.7	1.1	80.6	81.1
Heathlanes	SJ 620211	Permo-Triassic sandstones	1971	0.5	2.1	63.4	64.2
Nuttalls Farm	SK 067012	Permo-Triassic sandstones	1974	0.5	0.8	130.7	131.6
Peggy Ellerton	SE 454396	Magnesian Limestone	1968	1.2	1.3	37.4	37.8
Alstonfield	SK 129555	Carboniferous Limestone	1974	30.6	45.7	216.2	217.5

outcrop areas recoveries continued well into 2001 with maxima registered as late as May; through the spring groundwater levels commonly remained well above previous maxima (e.g. at Heathlanes in the Permo-Triassic sandstones of Shropshire).

Magnitude of the groundwater conditions experienced in 2000/01

The Hydrological Summaries for the UK for the September 2000 - April 2001 period provide details of groundwater levels at index sites throughout the country; the summaries for December and February, in particular, testify to the remarkably high water-tables throughout the major aquifers. Table 6 lists maximum groundwater levels recorded during 2000/01 for a selection of representative wells and boreholes; in each case the previous maximum level was exceeded - commonly by large margins. For Compton (in the Chalk of West Sussex), the late-2000 peak exceeded all recorded levels in a series from 1894 and at Stonor, in the Chilterns, levels in 2000/01 exceeded the previous maximum for more than five months. Foot and Mouth restrictions limited the availability of data for many observation boreholes in the Permo-Triassic sandstones but it is clear that new maximum levels were registered over wide areas (for example in the West Midlands and the Eden Valley). By the early spring, record groundwater levels also characterised a number of minor aquifers in eastern England (including the Norfolk Drift).

A further measure of the rarity of the groundwater conditions is provided by the remarkable peak flows recorded in springs and rivers reliant mainly on groundwater outflows. Spring outflows commonly reflect recharge patterns over several years and, as a consequence of this persistence, estimates of return periods need to be treated with particular caution. Nonetheless, the exceptional return periods associated with the highest flows in, for example, the Ewelme Brook (draining the Chalk) and Meese (Permo-Triassic sandstones) testify to an event of severe-to-extreme magnitude - see Table of peak flows. Winter runoff for such rivers commonly exceeded previous maxima by very wide margins - even for rivers with flow records of over 40 years. The combination of evidence, including directly measured groundwater level data for a small network of boreholes in the Chalk with records extending back more than 100 years, indicates that the 2000/01 conditions were without parallel in the 20th century.

Spring flows and groundwater flooding

The rapidly rising groundwater levels in late-2000 and early 2001 were accompanied by increased drainage from the aquifers, via springs, seepages and through stream beds - causing remarkably high flows in rivers draining from permeable catchments, Chalk downland in particular. Outstanding peak flows for rivers in the South Downs (e.g. the Itchen) during December 2000 (see Table of peak flows) were a direct result of significant periods of sustained recharge. In a number of other spring-fed rivers, including the Kennet and Dorset Stour, December runoff totals were without recorded precedent for any month. The Lavant, an intermittent river which flows through Chichester, was dry in early October 2000, but by mid November the river was flowing bankfull. A major and prolonged pumping operation was then necessary to protect parts of Chichester from inundation[4].

As water-tables reached the surface during December - and maintained high levels through the winter period - the effects of groundwater flooding were experienced more widely. Significant flows occurred in many normally ‘dry’ valleys and spring outflows were reported from the upper reaches of permeable catchments where surface flows have very rarely been recorded (e.g. in parts of the Chilterns). In southern England many localities remote from the low-lying floodplains were severely affected by groundwater flooding. In areas such as the Berkshire Downs and Chilterns prolonged flooding of house basements was common, together with localised road flooding where drainage ditches and culverts were unable to cope with the abundant outflows from the springs and winterbournes. In some areas (for example, Marlow in Bucks) flows across roads and into basements did not seriously reduce until the prolonged periods of dry weather in May and June 2001.

References

1. Gregory, J.M., Jones, P.D. and Wigley, T.M.L. 1991. Precipitation in Britain: an analysis of area-average data updated to 1989. International Journal of Climatology, vol 11, pp331-345.

2. Environment Agency. 2001. Lessons Learned: Autumn 2000 floods. Environment Agency, Bristol, 56pp, ISBN 1857055063.

3. Boardman, J. 2000. Don't blame the climate: Why the current floods are not all caused by global warming. The Guardian (Society section), 8th November 2000, p9.

4. Environment Agency, Southern Region. 2001. Autumn 2000 Floods Review, Regional Report. EA Southern Region, February 2001.

5. Environment Agency. 2000. Selby 'lake' now bigger than Windermere. EA Press Release 206/00, 9th November 2000, 2pp.

6. Environment Agency, Thames Region. 2001. Thames Region Hydrological Summary, March 2001. Thames Region Water Resources, April 2001, 9pp.

7. Rodwell, M.J., Rowell, D.P. and Folland, C.K. 1999. Oceanic forcing of wintertime North Atlantic Oscillation and European climate. Nature, vol 398, p320.

8. Institute of Hydrology. 1999. Flood Estimation Handbook (5 volumes). Institute of Hydrology, Wallingford.

9. Howorth, B., Mowbray, B.E., Haile, W.H. and Cubley Crowther, G. 1948. The Spring Floods of 1947. Journal of the Institution of Water Engineers, vol 2, no 1, February 1948, pp12-35.

10. McLean, W.N. 1953. The Lynmouth Flood of 15th August 1952. Journal of the Institution of Water Engineers, vol 7, no 2, March 1953, pp157-9.

11. Robinson, D.N. 2000. The Louth Flood - The story of the events of Saturday, 29th May 1920. The Louth Naturalists', Antiquarian and Literary Society, Louth, Lincolnshire. Updated version of original 1995 edition, 48pp.

12. Horner, M.W. and Walsh, P.D. 2000. Easter 1998 floods. Journal of the Chartered Institution of Water and Environmental Managers, vol 14, December 2000, pp415-418.

13. CEH, Wallingford. 2000. Hydrological Summary for the United Kingdom, November 2000. CEH Wallingford and the British Geological Survey, 12pp.

14. Hough, M.N. and Jones, R.J.A. 1996. The United Kingdom Meteorological Office rainfall and evaporation calculation system: MORECS version 2.0 - an overview. Hydrology and Earth Science Systems, Vol 1(2), 227-239.

Location Map

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