1990 – A YEAR OF FLOODS AND DROUGHT

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In January 1989 the Department of the Environment requested that the Institute of Hydrology and the British Geological Survey jointly re-activate a national hydrological monitoring programme and provide monthly reports dealing with rainfall, river flows and groundwater levels. A principal objective of this programme is to identify the development of drought conditions and to assess regional variations in intensity.

Most of the hydrometric data featured in the monthly reports are furnished by the regional divisions of the National Rivers Authority (NRA) and the River Purification Boards (RPBs). Rainfall, evaporation and soil moisture information are provided by the Meteorological Office and, from the summer of 1990, reservoir contents data have been supplied by the Water Services PLCs. Much of the material presented in the following article have been assembled as part of the ongoing national monitoring programme; the article also draws on data and figures presented in other sections of the 1990 Yearbook. Some of the data – especially those relating to the extreme range of river flow – may be subject to future review.

Background

For Great Britain as a whole, the decade beginning in 1980 was the wettest on record. Generally, the temporal distribution of the rainfall was also beneficial from a hydrological point of view – precipitation totals tending to be considerably higher in the winter when evaporation losses are modest[1]. Although a notable spring/summer drought afflicted much of western and northern Britain in 1984, the concern for water resources generated by the extreme drought of 1975/76 was largely dissipated over the ensuing dozen years. For most of this period, and in most areas, river flows and groundwater levels were above, often well above, the seasonal mean and low flows in particular were significantly greater than those registered in the early and mid-1970s and the mid-1960s. However, in parts of eastern and southern Britain an extended period of rainfall deficiency, beginning as early as the spring of 1988, laid the foundation for several notable drought episodes. In some eastern regions these episodes merged into a remarkably sustained period of rainfall deficiency, elsewhere the drought conditions were punctuated by several very wet interludes.

The Winter of 1989/90

For the second successive year the limited autumn rainfall and exceptionally dry soil conditions combined to greatly delay the recovery of river flows and groundwater levels in the latter half of 1989. Severe drought conditions afflicted much of eastern and southern England at the beginning of December 1989[2]; the depressed water-tables throughout most major aquifers was a matter of particular water resources concern. Heavy and sustained rainfall from mid-December 1989 helped to change the complexion of the drought and the transformation continued into 1990[3]. Several damaging storms in late January 1990 heralded a remarkably wet February which concluded the wettest winter (December-February) on record for Great Britain, it was also one of the warmest. In all but a few eastern areas, where the recovery in groundwater levels needed to be generated from an extremely low base, rainfall over the ten weeks to the end of February served to effectively terminate the drought. Although abundant rainfall characterised most regions, winter precipitation was especially notable in Scotland. The 1989/90 winter rainfall total for Scotland – approximately 640 mm – was the highest in the 121-year Scottish rainfall series. The January-March 1990 accumulation was even more remarkable. Each of the three individual monthly rainfall totals ranks among the highest ten in a series from 1869. Some localities in western Scotland recorded precipitation on each of the first 89 days of the year[4]. The three-month rainfall total to the end of March, currently assessed at 791 mm, is easily the highest for *any* three-monthly accumulation. This extraordinarily wet beginning to the year resulted in a very sharp upturn in runoff rates and caused persistent floodplain inundation. It also helped to extend an exceptional series of wet winter half-years (October-March) in Scotland; eight of the twelve wettest on record have occurred since 1978.

February 1990

With regard to river flows and groundwater levels, February 1990 has no modern precedent. Most catchments were saturated as a result of the December/January rainfall and thus very vulnerable to further precipitation (and, in northern Britain, to snowmelt). In the event, the February rainfall total was the highest on record for Great Britain and was closely comparable with that of October 1967 – the wettest month in the last 30 years. Over wide areas, February rainfall totals were three or four times the long-term average. River flows responded very briskly. Before the end of the first week, rivers were in spate throughout the great majority of the United Kingdom. Floodplain inundation was very widespread and rivers remained at bankfull, or above, for extended periods. A measure of the transformation over the winter is provided by the flows in the River Itchen, a chalk stream in southern England, which remained at bankfull through February having recorded its lowest ever naturalised daily flow (allowing for the immediate effects of groundwater augmentation) during December 1989. Many gauging stations recorded new maximum February mean flows and in a significant minority of catchments absolute monthly runoff records were established.

Remarkably high runoff totals were registered in Scotland. Precipitation totals for January 1990 exceeded twice the average in western and central areas and further rainfall in early February, associated with a moist, and warm, south-westerly airstream, triggered notable flood events throughout much of the country. From the 4th, the mild conditions induced a thaw which was especially rapid on windward slopes – snowmelt made a substantial contribution to most of the early February flood events in northern Britain. Subsequently, sustained rainfall maintained flows at, or above, bankfull for lengthy periods – over ten weeks in extreme cases. The widespread flooding, especially in northern Scotland, resulted in the massive disruption of road and rail transport, the isolation of villages and farms and substantial damage in both rural and urban areas (see cover and Plate 1). Some farmland, particularly in the Grampian region, was inundated for many weeks – floodbanks having been extensively breached. The magnitude of the February flooding was exemplified on the Tay – the UK's largest river in terms of discharge. Antecedent precipitation had been particularly heavy in the western headwaters – at the Lochy power station 518 mm was recorded over the 25 days ending on the 4th February. With the catchment saturated and little unused storage remaining in lochs and reservoirs, the Tay was in spate from late-January[5]. Further rainfall and the associated thaw in early February produced a peak flow rate measured at the Ballathie gauging station of 1746 m^3s^{-1}, this despite considerable attenuation of the flood due to the breaching of upstream flood-

Plate 1. Damage following the February 1990 flooding in Tayside.
Photo: Tay River Purification Board.

banks. The associated daily mean flow (1647 m^3s^{-1}) exceeded the highest daily flow held on the Surface Water Archive; the monthly mean for February created a new record (as did the 1990 annual runoff total). The Clyde was one of a number of westward-draining Scottish rivers which, in February, comfortably exceeded its previous maximum monthly mean flow. Flooding was extensive in catchments draining from the Highlands and water levels in Loch Lomond rose close to 9.5 metres a.OD – exceeding the previous maximum in a record extending back to 1947[4]. (Levels continued to rise reaching a peak of 10.075 metres a.OD by the 11th March.)

Whilst peak flows were less notable in southern Britain, floodplain inundation was common and rivers remained in spate for lengthy periods. The contrast with the early winter flow rates was especially notable in chalk streams in central southern England. The February runoff totals for a number of rivers in the Wessex region, for instance, easily surpassed the preceding maximum for any month and on the River Wylye (at South Newton) daily mean flows exceeded the previous maximum for fourteen days. Flows remained close to, but generally below, critical discharge rates for more than a fortnight over wide areas. Any additional rainfall in February, or a temporal redistribution of that which did fall, would have produced relatively severe flooding. In the Thames valley significant flooding was confined to the middle reaches but daily mean flows at Kingston exceeded 300 m^3s^{-1} for 15 successive days in February, the longest sequence since the major flooding of March 1947. Overbank flow was also a feature in the Severn basin for extended periods.

Based on a representative network of 33 catchments, the total freshwater outflow from mainland Great Britain in February 1990 was the highest – for any month – in at least 25 years. Figure 9 illustrates monthly outflows over the period 1965–90. The primacy of the February runoff reflects both the exceptional geographical spread of spate conditions and the very mild weather which generated a rapid,

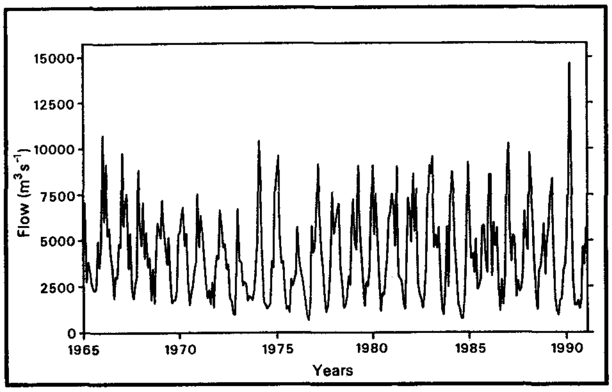

Figure 9. Monthly outflows from mainland Great Britain 1965–90.

and general, thaw early in the month. Combinations of heavy rainfall and snowmelt have produced regional runoff totals considerably in excess of those recorded in February 1990 – for example in March 1947 runoff was two or three times greater throughout much of southern England. However, as with other more recent such events, the 1947 thaw was not synchronous throughout Britain. The snowmelt contribution in February 1990 partly accounts for the very modest monthly 'loss' (rainfall – runoff, see Table 4). A further factor was the especially heavy rainfall over the last three days of January much of which boosted estuarine outflows in early February. Runoff in October 1967, which was marginally wetter than February 1990, provides an illustration of the moderating influence that relatively dry soils can exert.

TABLE 4 HIGHEST MONTHLY RUNOFF AND RAINFALL FROM GREAT BRITAIN (1960–1990)

Rank	Month	Year	Runoff (mm)	Loss (mm)	Rainfall (mm)	Rank
1	FEB	1990	165	29	194	(2)
2	DEC	1965	133	33	166	(14)
3	JAN	1974	130	29	159	(19)
4	DEC	1986	128	61	189	(3)
5	JAN	1988	122	47	169	(12)
6	DEC	1966	122	36	158	(20)
7	JAN	1975	120	43	163	(15)
8	JAN	1983	119	17	136	(48)
9	DEC	1979	113	61	174	(7)
10	MAR	1979	113	35	148	(34)
11	NOV	1984	112	63	175	(6)
12	MAR	1981	112	41	153	(24)
13	NOV	1982	110	51	161	(18)
14	OCT	1967	110	85	195	(1)
15	JAN	1984	109	62	171	(11)

The Recovery of Groundwater Levels in early 1990

The rapid elimination of most remaining soil moisture deficits in late December 1989 throughout the great majority of the English lowlands paved the way for dramatic increases in groundwater levels in January and February 1990. At the Chilgrove (West Sussex) observation borehole, which is thought to have the longest sensibly continuous record (from 1836) in the world, the water-table recovery began in mid-December when levels in the Chalk had declined to within a few centimetres of the period-of-record minimum (recorded in 1976). The ensuing 40 metre rise, over an eight-week period, has no close parallel – the rate of recovery appreciably exceeded the notable rise following the end of the 1976 drought. As a consequence spring flows broke and winterbournes began to flow for the first time in some locations since the spring of 1988. However, spatial variations in recharge amounts over the 1989/90 winter varied greatly. In parts of eastern England only a modest rise in groundwater levels occurred over the December-February period. At the Fairfields observation borehole in Suffolk, for instance, the 1989/90 recharge was estimated at less than ten per cent of the long-term average. Infiltration was also minimal over the previous winter; as a consequence groundwater levels entering the spring of 1990 were well below any previously recorded for the time of year (see Figure 18 – page 168).

The 1990 Drought

The spring of 1990 was, for England and Wales, the driest since 1893 and the warm, sunny weather encouraged very high evaporation rates. River flows remained notably high during March in Scotland but, in southern Britain, rivers were in steep recession from late-February and water-tables declined rapidly. This further hydrological transformation served to underline the particular importance of spring (March-May) rainfall in relation to water resources. Most western reservoirs were at capacity by the end of January. Many of the smaller impoundments could have been filled again over the ensuing three weeks and, in Wales especially, controlled releases were necessary to provide a measure of flood alleviation storage. The benefit of abundant runoff early in the year was however, counteracted by the very early onset of the seasonal drawdown as demand exceeded replenishment. Thus by mid-April reservoir contents at Stithians (Cornwall), for instance, fell below those registered in 1976 (when capacity was never reached but stocks were recovering slowly throughout the early spring). Although in deeper observation boreholes the time taken for water to percolate down to the water-table delayed the winter peak somewhat, a similar picture emerged in relation to groundwater levels which displayed exceptionally steep recessions from early March.

TABLE 5 NATIONAL AND REGIONAL RAINFALL TOTALS FOR SELECTED PERIODS, 1988-90

		MAR. - SEP. 90	Est. R.P. (yrs)	JAN. - SEP. 90	Est. R.P. (yrs)	AUG. 89 - SEP. 90	Est. R.P. (yrs)	NOV. 88 - SEP. 90	Est. R.P. (yrs)
England and Wales†	mm	292		567		959		1478	
	%	59	120–180	88	2–5	88	5–10	85	15–20
NRA REGIONS									
North West	mm	467		857		1331		2117	
	%	70	30–40	100	<2	91	2–5	91	5–10
Northumbria	mm	323		570		848		1304	
	%	66	40–60	90	2–5	80	15–25	77	70–100
Severn Trent	mm	240		455		806		1253	
	%	55	120–180	81	5–10	88	5–10	85	10–20
Yorkshire	mm	279		509		790		1276	
	%	61	50–80	85	5–10	79	15–25	80	40–50
Anglian	mm	194		321		561		919	
	%	56	140–200	72	20–30	77	20–40	79	40–60
Thames	mm	187		393		708		1082	
	%	48	>200	78	5–10	85	5–10	81	20–30
Southern	mm	209		466		803		1184	
	%	51	150–200	86	2–5	86	5–10	78	40–50
Wessex	mm	244		526		942		1391	
	%	53	120–170	88	2–5	91	2–5	84	10–20
South West	mm	384		817		1430		2052	
	%	65	30–40	101	<2	102	2–5	90	5–10
Welsh	mm	419		874		1515		2298	
	%	61	70–100	95	2–5	96	2–5	91	5–10
Scotland	mm	868		1412		2035		3158	
	%	117	5–10	143	≥200	120	40–60	116	40–60
RIVER PURIFICATION BOARDS									
Highland	mm	1222		1880		2666		4201	
	%	140	150–200	161	≥200	131	≥200	129	≥200
North-East	mm	495		752		1061		1621	
	%	89	2–5	104	2–5	87	5–10	83	30–50
Tay	mm	590		1116		1612		2491	
	%	88	2–5	127	20–30	108	2–5	104	2–5
Forth	mm	561		1005		1448		2219	
	%	91	2–5	127	30–40	108	2–5	104	2–5
Tweed	mm	417		762		1098		1662	
	%	75	10–20	106	2–5	91	2–5	87	10–15
Solway	mm	624		1163		1739		2687	
	%	83	5–10	118	5–10	102	2–5	99	2
Clyde	mm	1036		1693		2489		3799	
	%	121	10–15	150	≥200	126	80–100	121	80–120

* R P = Return Period. % = percentage of the 1941–70 average

Return period assessments are based on tables provided by the Meteorological Office*. These assume a start in a specified month; return periods for a start in any month may be expected to be substantially less. 'Wet' return periods are underlined.

The Tabony tables reflect rainfall totals over the period 1911–70 only and the return period estimates assume a sensibly stable climate.

† Based on the series derived by the Climatic Research Unit of the University of East Anglia[9].

* Tabony, R C, The Variability of long duration rainfall over Great Britain, Scientific Paper No. 37, Meteorological Office (HMSO).

Whilst, in most areas, the summer (June-August) was not notably dry, by late-September an intense seven-month drought extended across much of southern Britain. Large parts of central, southern and eastern England recorded less than half the average rainfall over this period (see Figure 10). The estimated return periods associated with the rainfall deficiencies exceeded 100 years in most regions of England (see Table 5). These estimates relate to the period March to September only, if rainfall accumulations over *any* seven month period are considered then the 1990 regional figures may be seen to be appreciably less rare. Nonetheless, for England and Wales as a whole, the March to September period was the driest (for that period) in a general rainfall series beginning in 1767. Considering *any* seven-month sequence there have only been three drier periods (two in 1976 and one during the 1921 drought) this century. The hydrological impact of the drought also reflected the very substantial long term rainfall deficiencies in eastern Britain.

The hot and sunny conditions throughout the extended summer stimulated increased demand for water (especially for gardens) and triggered measures to restrict usage – mostly hose-pipe bans but restrictions on spray irrigation were applied in parts of southern and eastern England. Whilst in terms of public perception the drought assumed a high profile principally in the summer, the hydrological character of the drought reflected the warm conditions – and associated high evaporation rates – throughout the year. MORECS (Meteorological Office Rainfall and Evaporation Calculation System[6]) data demonstrate that the record potential evaporation (PE) losses registered in 1989 were eclipsed over wide areas and southern Britain experienced a lengthy period with little or no effective rainfall[7]. Table 6 ranks MORECS annual PE and Actual Evaporation (AE) totals for two grid squares (40 km by 40 km) in southern Britain. The exceptional nature of the potential evaporation losses in 1989 and 1990 is immediately evident. Largely, the rankings reflect the notable warm and sunny conditions which characterised the two-year period. Annual average temperatures for 1990 and 1989 rank first and second respectively in the central England temperature series which begins in 1659[8].

The complex interplay of factors affecting evaporation losses produced substantial differences in regional and local annual PE and AE totals. Potential evaporation totals for 1990 exceeded 650 mm over

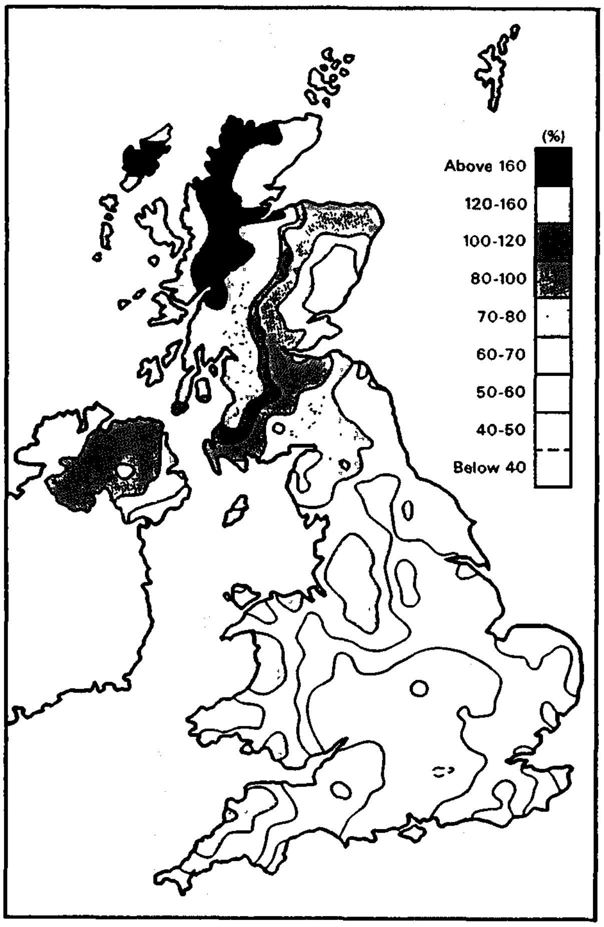

Figure 10. March – September rainfall in 1990 as a percentage of the 1941–70 average. Source: Meteorological Office.

TABLE 6 RANKED MORECS ANNUAL PE AND AE TOTALS (FOR A GRASS COVER)

	MORECS SQUARE 128 (CAMBRIDGESHIRE)			MORECS SQUARE 134 (CENTRAL WALES)	
YEAR	PE (mm)	AE (mm)	YEAR	PE (mm)	AE (mm)
1968	540	517	1979	483	462
1978	543	462	1963	491	488
1981	549	483	1978	492	479
1987	553	518	1987	494	484
1972	555	421	1981	496	465
1963	563	480	1968	498	490
1971	568	483	1971	498	490
1969	569	489	1962	502	480
1977	573	467	1972	504	491
1966	578	543	1966	504	498
1965	579	488	1969	504	484
1979	580	462	1980	509	495
1980	580	508	1965	510	506
1988	581	516	1964	513	486
1962	582	464	1986	515	493
1982	586	513	1973	516	505
1985	587	512	1988	520	517
1983	590	473	1970	520	507
1973	591	512	1985	523	519
1984	606	466	1977	524	509
1986	619	540	1982	527	510
1964	621	445	1961	534	490
1974	621	518	1983	538	495
1967	626	523	1967	539	528
1961	636	452	1974	540	527
1970	638	463	1975	563	505
1975	646	485	1976	565	404
1976	636	317	**1990**	**571**	**486**
1989	**689**	**495**	**1989**	**584**	**478**
1990	**725**	**402**	1984	586	502

TABLE 7 CATCHMENT RUNOFF FOR SELECTED PERIODS 1988-90

River/ Station Name	Feb 1990		Sep 1990		4/90 to 9/90		1/90 to 9/90		10/89 to 9/90		11/88 to 9/90	
	mm %LT	rank /yrs	mm %LT	rank /yrs	mm %LT	rank /yrs	mm %LT	rank /yrs	mm %LT	rank /yrs	mm %LT	rank /yrs
Tay at	349	38	42	10	299	8	1172	38	1441	37	2616	37
Ballathie	318	/38	59	/38	83	/38	158	/38	129	/38	123	/37
South Tyne at	208	28	23	5	107	1	533	18	707	10	1194	4
Haydon Bridge	308	28	44	/27	45	/27	109	/27	94	/27	83	/25
Derwent at	37	17	5	1	48	1	131	2	165	1	340	1
Buttercrambe*	93	/29	36	/29	42	/29	54	/29	50	/29	53	/28
Dove at	78	25	11	5	88	2	275	3	378	2	743	3
Marston on Dove	143	/29	45	/28	51	/28	78	/28	75	/28	76	/26
Lud at	21	4	8	4	61	4	115	4	138	3	282	2
Louth	59	/22	70	/23	51	/22	52	/22	51	/22	54	/21
Little Ouse at	18	9	4	2	36	4	81	4	103	4	238	2
Abbey Heath	79	/22	53	/23	54	/23	60	/22	58	/22	70	/21
Mimram at	15	33	5	4	48	6	88	12	109	10	210	7
Panshanger Park	128	/38	62	/38	76	/38	88	/38	87	/37	86	/36
Thames at	71	106	5	11	50	19	182	53	236	47	398	28
Kingston (natr.)	216	/108	56	/108	63	/108	100	/108	96	/107	83	/106
Coln at	100	27	10	2	111	4	338	15	402	10	646	6
Bibury	189	/27	70	/27	72	/27	107	/27	102	/27	83	/26
Great Stour at	51	24	6	1	59	2	151	4	193	4	352	1
Horton	152	/26	43	/26	56	/24	70	/24	65	/23	60	/21
Itchen at	74	32	20	3	177	5	351	14	423	7	732	2
Highbridge + Allbrook	153	/32	76	/32	85	/32	98	/32	91	/32	81	/31
Stour at	156	18	5	1	62	3	331	15	429	11	668	4
Throop Mill	281	/18	42	/18	58	/18	119	/18	108	/17	87	/16
Tone at	170	30	7	2	60	2	356	16	488	15	787	4
Bishops Hull	235	/30	45	/30	47	/30	105	/29	102	/29	85	/28
Severn at	121	68	6	6	51	1	297	31	432	30	736	11
Bewdley	212	/69	27	/70	40	/70	98	/69	96	/69	85	/68
Teme at	109	19	2	1	32	1	252	7	374	8	581	2
Knightsford Bridge	209	/20	24	/21	35	/21	96	/20	100	/20	80	/19
Cynon at	393	32	20	5	150	2	944	27	1480	28	2320	14
Abercynon	300	/32	29	/32	46	/32	122	/32	119	/32	98	/30
Dee at	346	21	73	6	320	4	1147	11	1772	9	3014	5
New Inn	215	/21	53	/22	60	/21	102	/21	98	/21	88	/20
Lune at	280	28	30	6	174	2	777	18	1083	13	1948	8
Caton	302	/28	34	/28	47	/28	109	/28	96	/26	91	/24
Clyde at	224	27	36	10	204	11	771	27	939	25	1623	22
Daldowie	319	/27	62	/27	89	/27	159	/27	124	/27	113	/26

Notes (i) Except for the Thames, gauged flow data have been used.
(ii) Values are ranked so that lowest runoff is rank 1;
(iii) %LT means percentage of long term average (preceding the featured period).
*Includes the Stamford Bridge record (1961-73).

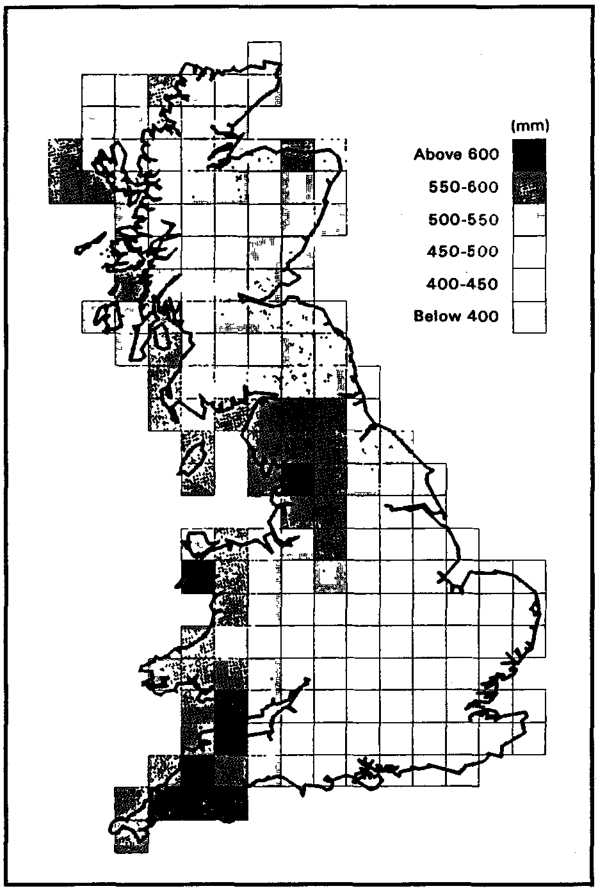

Figure 11. Actual evaporation (for grass) in 1990 – in millimetres. Data source: MORECS

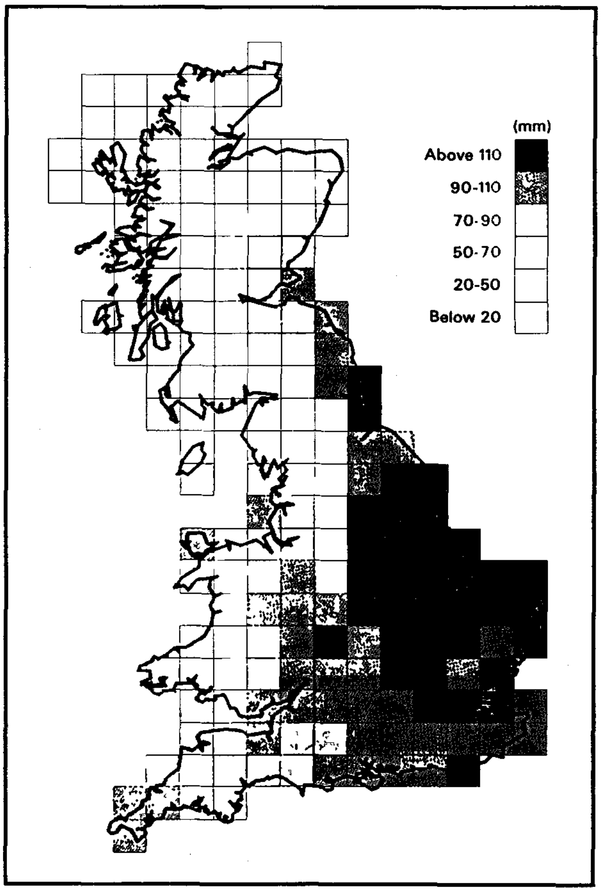

Figure 12. Soil moisture deficits (for grass) at the end of September 1990. Data Source: MORECS.

much of southern Britain (see Figure 3) and for the first three months of the year AE losses were close to, or at, record levels in most regions also. From April however shortfalls of AE relative to PE became substantial away from the wetter western and northern areas of Britain. For the year as a whole, AE losses (see Figure 11) were commonly the lowest since 1976 in the lowlands. By contrast, in much of western Britain AE totals were often the highest or close to the highest in the MORECS series. Thus transpiration losses were a more significant aggravating influence on the drought's development in the wetter regions of England and Wales than in the east where the dryness of the soils was of major hydrological significance. Figure 12 shows that very substantial SMDs were maintained well into the autumn throughout large parts of eastern and southern Britain; calculated deficits (for grass) exceeding 70 mm were maintained for over six months (two to three being more typical). MORECS deficits for the area around the Humber estuary exceeded the 70 mm threshold for approximately 12 months during the two years from January 1989; this is twice the average timespan and is unapproached in any other two-year period in a series from 1961. In many areas the late-September 1990 deficits were the equivalent of more than two months of average rainfall. Given the dry autumn in the east, one important effect was to greatly delay the onset of infiltration (see below).

Autumn 1990 runoff rates fell below the seasonal mean – by a considerable margin for rivers with flow records of less than about 25 years – throughout almost all regions. It is rare for such notably low flows to extend across almost all of Great Britain. The Dorset and Kent Stours were among a significant number of lowland rivers to establish new September minimum runoff totals (see Table 7). For the Thames, the September naturalised mean flow was the lowest since 1949 and the scale of the recession through the year was the greatest since 1947. Accumulated runoff totals over the water-year (October – September) were also amongst the lowest on record in eastern and southern catchments.

Whilst the annual minima recorded in 1990 were exceptional in relatively few catchments, the overall flow range was, in many areas, noteworthy. A few rivers, including the Ebbw and Rhymney (see Figure 13) in South Wales, recorded new instantaneous peak and minimum monthly flow rates within the space of only four months. Such exceptional volatility was rare but, taking a broad perspective, a general distinction could be made between rivers in northern and western Britain – and parts of Northern Ireland also

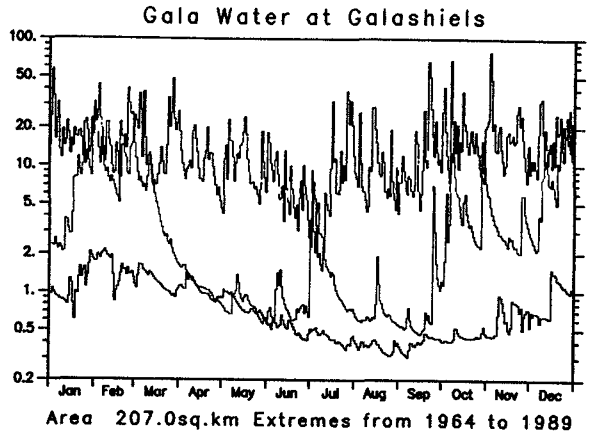

Figure 13a. 1990 river flows in the Tweed Basin. (the 1990 daily flow hydrograph is shown in blue, the period of record max. and min. daily flows in black)

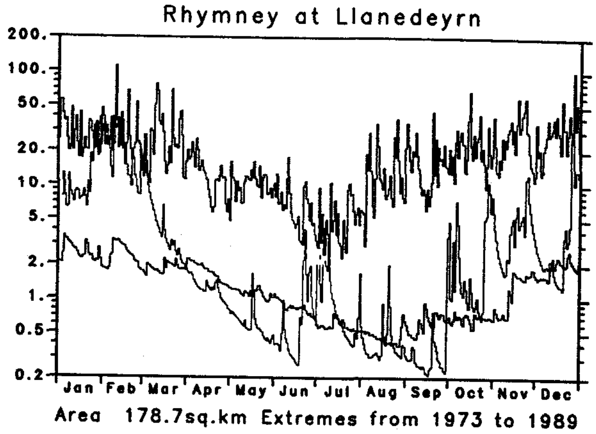

Figure 13b. 1990 river flows in South Wales.

– where 1990 witnessed an upward extension in the range of recorded flow rates in many catchments, and the downward extension which typified a substantial proportion of eastern lowland rivers.

Generally, early autumn flows were exceptionally low in both impervious catchments and more permeable catchments, often for the second or third successive year (see Plate 2). For many eastern rivers, summer and early autumn flow, patterns over 1989–90 contrasted sharply with those which characterised the preceding record. The flow duration curve for the River Derwent in Yorkshire (Figure 14) serves to emphasise the peculiar nature of flow patterns for 1989–90: flows were depressed throughout the range and the 95 per cent exceedance flow was less than 75 per cent of that for the preceding record. As with a significant proportion of eastern rivers, particularly those supported principally from groundwater, the low flow range has been largely redefined since 1988.

The accentuated seasonality implicit in the hydrographs featured on Figure 13 was even more exaggerated when the rainfall distribution is considered for the 12 months ending in September 1990; more than 60 per cent of the rainfall in some parts of England was attributable to a ten-week period in the winter. Such a distribution is more readily associated with, say, northern Portugal and climatic comparisons are made more compelling by the very mild winter of 1989/90 and the notably hot summers which preceded and followed it. The partitioning of rainfall between the winter and summer half-years in 1989/90 represents an extreme expression of a tendency which characterised much of the 1980s when the modest seasonality displayed by rainfall over much of the UK, was reinforced (see Figure 15). For England and Wales, the ratio of winter to summer half-year rainfall throughout much of the nineteenth century was close to unity. In the 1980s, the ratio commonly exceeded 1.3 and for 1989/90 the winter half-year rainfall was more than twice that of the ensuing summer for the first time in a series from 1767.

Plate 2. Low flow in the River Torridge at Torrington.
Photo: Paul Mason, NRA – South West Region.

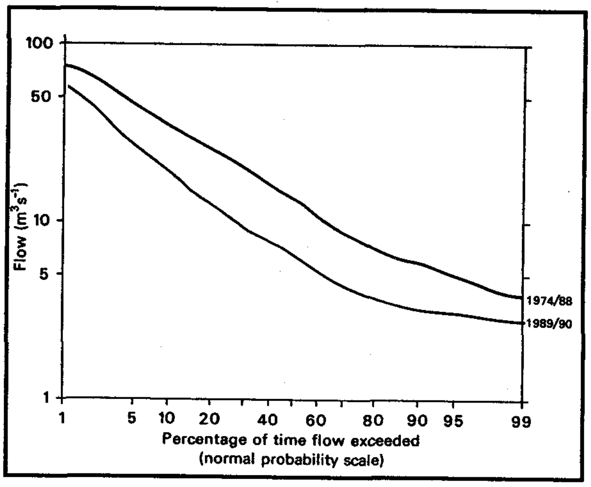

Figure 14. A comparison of flow duration curves for the River Derwent at Buttercrambe.

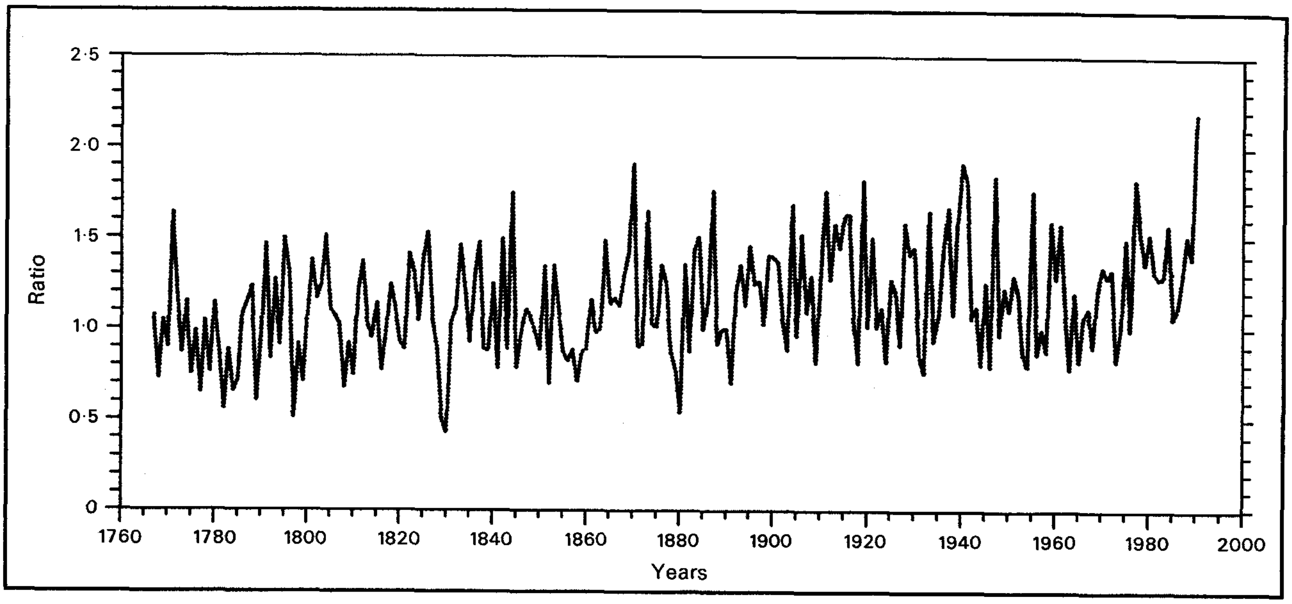

Figure 15. The ratio of winter (October – March) to summer (April – September) half-year rainfall for England and Wales.
Data source: The homogenised England and Wales rainfall series derived by the Climate Research Unit of the University of East Anglia[9].

Rainfall in October 1990 generated some increase in river flows in western and northern Britain. A number of rivers in southern Scotland were in spate by the end of the first week and peak flows in parts of the Forth and Tweed basins exceeded any previously recorded. As in the previous year however, the very dry lowland soils greatly limited the hydrological impact of the autumn rainfall and, in parts of central southern England and East Anglia, the drought increased in severity into the early winter. By late November, many spring-fed streams, and a large number of ponds, had remained dry for much of the preceding two years – the loss of amenity for extended periods since early 1988 had been considerable and was accompanied by a substantial, if temporary, loss of habitat for fish and other aquatic life. The shrinkage of drainage networks was exacerbated in some areas – for example in parts of the Chilterns, the North Downs, Dorset and East Anglia – by the impact of heavy groundwater abstraction on river flows. Generally the reduction in runoff, which is particularly evident in the headwaters, reflects long term increases in groundwater pumping often extending over 40 years or more. However, for much of the post-1976 period, the effects have been disguised or ameliorated by the preponderance of relatively wet winters.

Soils remained remarkably dry at the beginning of winter in 1990 in parts of southern and eastern England. On the basis of the results from a percolation model developed by the Thames region of the National Rivers Authority, the late-November SMDs rank as the highest in a 70-year series for parts of the Thames Valley. By early December, flows in the River Thames had fallen to the lowest for December since 1947 as the Thames Valley experienced its tenth successive month with below average rainfall. On a countrywide basis the outlook was least encouraging in water resources terms where the 1990 drought overlay a substantial long term rainfall deficiency – broadly the affected region embraced much of the South-East and East Anglia.

Widespread blizzards in the second week of December heralded a further change in weather conditions. A series of active depressions on a mild south-westerly airflow brought substantial rainfall to all areas and generally produced a transformation in river flows reminiscent of, but considerably less dramatic than, that witnessed a year earlier. The water resources outlook improved considerably by the year end and aquatic habitats began to take on a more familiar appearance. Nonetheless, in parts of the lowlands – especially in a zone extending from Kent to Lincolnshire – the drought was far from terminated. Groundwater levels in late December remained amongst the lowest on record and, with a much truncated period available for further recharge before accelerating evaporation rates in the spring signalled the beginning of the 1992 recession, there was every expectation that depressed groundwater levels and very modest baseflows in rivers would continue well into 1991.

The Severity of the Drought

Runoff

The accumulated catchment runoff totals presented in Table 7 provide a guide to the hydrological intensity of the drought over a variety of durations. The periods featured generally coincide with the ranges of months over which, at least in certain parts of Great Britain, the 1988–90 drought achieved its greatest severity. Mean flows for February and September 1990 are given to help quantify the scale of the runoff decline through the year. The quoted rankings refer to the specified periods only and provide clear evidence both of the length of the drought in the English lowlands and the remarkable spatial variation in runoff rates across Britain. This is particularly true in relation to the longer durations: accumulated runoff over the 23 months to September 1990 for gauging stations in eastern and southern England closely approached or superseded the previous lowest 23-month totals. In the same timeframe, outflows from rivers draining the Scottish Highlands were very abundant, sometimes unprecedented.

A more rigorous assessment of drought severity may be made if the low flow analyses are freed from the rather arbitrary constraints imposed by considering fixed sequences of days or months[10]. Thus whilst, for instance, the May to November 1990 mean naturalised flow for the Thames (at Kingston) was clearly the lowest, for that specified period, since the major structured alterations to the gauging station in 1951, three lower 7-month accumulations (albeit overlapping) were recorded during the 1976 drought. Where hydrometric records provide only a relatively short historical perspective, the longer term accumulations in 1989/90 remain very outstanding. The combined 1989 and 1990 runoff totals on the Yorkshire Derwent and the Lud (Lincolnshire), for example, are lower than any previous 24-month accumulations.

Generally, the length of period over which depressed flow rates were maintained was more exceptional than the short period minima registered in the summer of 1990. Over the latter half of the year flows throughout much of the lowlands – and extending north along the eastern seaboard – remained close to the seasonal minimum. Table 8 ranks the eight lowest annual n-day flows over a range of durations for three English gauging stations. For the Leven (a tributary of the Tees) the 1990 low flows were significantly less severe than those for 1976 over the shorter durations and, for periods exceeding about three months, the 1990 n-day minimum rank second to the sustained drought flows during 1964. However, over the longer durations both the 1989 and 1990 minimum flow sequences rank in the lowest three in a 31-year record. Whilst runoff patterns in nearby catchments suggest that exceptionally low flows would also have occurred in the Leven in 1959, there is no close precedent for such notably depressed runoff rates being registered in successive years. In Scotland, the 1989 and 1990 240-day minimum flows on the River Dee (at Woodend – not featured in Table 8) were each appreciably lower than any registered since the drought of 1976. Over the intervening period, summer flow rates generally remained healthy providing a pointed contrast in eastern Scotland with the early 1970s; the 240-day minima for each of the five years beginning with 1971 was below the corresponding flow for 1990.

In terms of flow characteristics the Hampshire Itchen, which has a stable regime, is very different from the responsive Leven but the low rankings in Table 8 for the 1989 and 1990 droughts are broadly similar. Augmentation of low flows (using groundwater) for significant periods in 1989–90 implies that the River Itchen data need to be treated with caution. Nonetheless, the presence of 1988 as well as 1989 and 1990 in the lowest six 240-day minima for the Highbridge/Allbrook gauging station testifies to a drought of considerable severity and remarkable duration.

TABLE 8 RANKED ANNUAL MINIMUM N-DAY FLOWS

River/Gauging station	30-day Year	30-day Mean flow m^3s^{-1}	60-day Year	60-day Mean flow m^3s^{-1}	120-day Year	120-day Mean flow m^3s^{-1}	240-day Year	240-day Mean flow m^3s^{-1}
River Leven	1976	0.121	1976	0.146	1964	0.239	1964	0.326
at Leven Br.	**1990**	**0.186**	**1990**	**0.194**	**1990**	**0.272**	**1990**	**0.419**
Period of	1964	0.188	1964	0.202	**1989**	**0.343**	**1989**	**0.459**
record:	1960	0.228E	**1989**	**0.280**	1975	0.331	1962	0.590
1960–90	**1989**	**0.240**	1975	0.284	1961	0.370	1970	0.613
	1972	0.254	1970	0.292	1977	0.384	1976	0.665
	1965	0.256	1961	0.296	1972	0.392	1975	0.693
	1975	0.267	1972	0.298	1962	0.399	1961	0.745
River Wissey	**1990**	**0.226**	**1990**	**0.247**	**1990**	**0.282**	**1990**	**0.493**
at Northwold*	1976	0.281	1976	0.301	**1989**	**0.390**	**1989**	**0.697**
Period of	**1989**	**0.341**	**1989**	**0.355**	1976	0.409	1976	0.741
record:	1964	0.426	1964	0.472	1964	0.540	1959	0.818
1956–90	1957	0.431	1957	0.478	1959	0.565	1964	0.860
	1959	0.444	1959	0.479	1957	0.608	1956	0.920E
	1986	0.503	1974	0.567	1974	0.674	1957	0.941
	1960	0.534	1986	0.569	1960	0.678	1960	1.050
River Itchen	1976	2.303	1976	2.389	1976	2.520	1976	3.002
at	**1989**	**2.575**	**1989**	**2.688**	**1989**	**2.796**	1973	3.112
Highbridge/	1959	2.637	1973	2.738	1973	2.804	**1989**	**3.313**
Allbrook	1973	2.650	1959	2.757	**1990**	**2.873**	**1990**	**3.341**
Period of	**1990**	**2.736**	**1990**	**2.777**	1959	3.026	1965	3.826
record:	1961	2.956	1961	3.102	1978	3.267	1988	3.940
1959–90	1978	3.057	1972	3.120	1961	3.301	1959	3.965
	1987	3.064	1978	3.134	1978	3.303	1962	3.971

E = estimated

*Changes to the arrangement of the gauging facilities imply that there is not full equivalence between the pre- and post-1980 flow data. The featured rankings are, however, largely unaffected.

The River Wissey drains a predominantly agricultural catchment developed on the Chalk (covered in some areas by Boulder Clay) of East Anglia. Spray irrigation has increased appreciably in recent years but overall the net impact of abstrations and discharges on the flow regime is relatively minor.The catchment lies in a zone – extending broadly from Lincolnshire to Kent – where the 1990 drought achieved its greatest severity. Although the absolute daily minimum (recorded in 1976) on the Wissey was not superseded during the recent drought, the 1990 minima are outstanding over durations in excess of about a month. Excluding 1976, the n-day minima for 1990 were little over half the corresponding pre-1989 minima. This, together with the unprecedented runoff deficiencies recorded throughout 1990 – December was the 29th successive month with below average mean flows – points to a drought of a very exceptional magnitude.

Groundwater levels

A general co-incidence may be identified between the regions with the largest long term (more than two years) rainfall deficiencies in late 1990 and the outcrop areas of the major aquifers – the Chalk especially. It is to be expected therefore that in groundwater terms the 1989–90 drought would be particularly severe. The low aquifer storages which characterised large areas in the latter half of 1990 reflect both the sustained recession in levels from the early spring and the very limited recharge in eastern areas since early 1988 when water-tables stood well above average throughout most major aquifers. Recharge during the 1988/89 winter half-year was the lowest since 1975/76 over large areas and foreshadowed a further lengthy period of limited rainfall and high evaporative losses which provided little opportunity for levels to be restored to their normal range. In some regions groundwater abstraction was an exacerbating factor. Many boreholes recorded levels close to, or below, the seasonal minimum in the autumn and early winter of both 1989 and 1990; the hydrographs presented on Figure 18 testify also to the exceptional range of level variation over the 1988–90 period.

Table 9 ranks annual minimum levels for two of the longest borehole records on the national groundwater level archive maintained by the British Geological Survey; both boreholes monitor levels in the Chalk and Upper Greensand aquifer, one in Sussex (at Compton) the other towards the northern limit of the Chalk outcrop in the Yorkshire Wolds (Dalton Holme). At Compton, most of the noteworthy twentieth century droughts over southern Britain feature in the twenty ranked minima. The early to mid-1970s figure prominently: a sustained rainfall deficiency in the initial years of the decade (when winter recharge was limited) resulted in a succession of low annual minima. Subsequently, levels recovered only to plunge once more during the very intense drought of 1975/76 when winter recharge was minimal. The recent annual minima failed to eclipse that of 1976 but there are no lower December minimum in the 96-year Compton record than those registered in 1989 and 1990, although they closely equate to that registered in 1973. The annual minimum levels for 1989 and 1990, both also recorded in December, at the nearby Chilgrove well were even more outstanding. Only in 1973, in a record from 1836, has an equivalent winter minimum to those of 1989 and 1990 been recorded.

In Humberside the drought achieved an even greater intensity. At Dalton Holme groundwater levels have been measured continuously since 1889 and appear to have been little affected by pumping in the vicinity. This important record affords a means of comparing periods of severe groundwater depletion in the Chalk of eastern Yorkshire and Humberside. Considering the full 101-year record, the annual fluctuations indicate that recharge over the 1988/89 winter ranks eighth lowest and that for 1989/90 fourteenth. However, when the combined recharge estimates for successive winters are examined, that for 1988–90 ranks third lowest behind 1912–14 and 1947–49. In the latter two drought episodes, the water-table stood at an historically high level prior to the onset of the sustained recessions. This factor largely explains why groundwater levels in the earlier droughts failed to fall to the very depressed levels recorded in 1990.

TABLE 9 RANKED ANNUAL MINIMUM GROUNDWATER LEVELS IN THE CHALK AND UPPER GREENSAND

Rank	COMPTON (1893–1990) Year	COMPTON (1893–1990) Min. Level (m.OD)	DALTON HOLME (1889–1990) Year	DALTON HOLME (1889–1990) Min. Level (m.OD)
1	1976	27.64	**1990**	**10.34**
2	1974	27.84	**1989**	**10.73**
3	1973	27.92	1988	11.51
4	**1990**	**27.96**	1905	11.58
5	**1989**	**28.24**	1922	11.61
6	1972	28.88	1965	11.74
7	1934	29.00	1921	11.81
8	1921	29.00	1906	11.84
9	1969	29.02	1976	11.87
10	1978	29.27	1984	11.88
11	1959	29.32	1942	11.89
12	1970	29.41	1949	12.09
13	1971	29.53	1986	12.14
14	1944	29.70	1954	12.17
15	1922	29.70	1950	12.32
16	1975	29.95	1985	12.36
17	1984	30.00	1943	12.39
18	1947	30.10	1953	12.47
19	1919	30.10	1929	12.47
20	1979	30.17	1946	12.62

The location of the two boreholes are shown on page 165.

Table 9 confirms that the annual minima for 1988, 1989 and 1990 at Dalton Holme rank third, second and first in the entire series. Whilst, a monthly monitoring cycle may, on occasions, not capture the full range of groundwater variation, it is clear that the 1988–90 groundwater drought in the southern Wolds (and over a larger area extending south into East Anglia) is without parallel in the twentieth century. Evidence from monitoring boreholes in other Yorkshire boreholes suggest that the 1990 depletion appears, for Yorkshire as a whole, to be easily the most severe on record – most observation borehole records date from the late-1960s and early-1970s.

To the south, assessments of drought severity in 1990 are hampered by the dearth of long continuous borehole records (unaffected by pumping) and, more significantly, the fact that no real termination to the drought could be recognised at year end. In many eastern areas, further limited recharge over the 1990/91 winter is indicative of even lower groundwater levels in prospect. It is clear that the full magnitude of the groundwater drought in the English lowlands will not become evident until late-1991 at least. Nonetheless, by December 1990 levels throughout large parts of East Anglia, and extending into neighbouring regions, had declined to close to, or below, the minimum on record. In many areas the modest subsequent recharge resulted in the 1991 recessions beginning at a similar level to those of the spring of 1973 – previously the most severe period of groundwater depletion in the recent past throughout much of eastern England. Although the groundwater drought generally decreased in severity away from the English lowlands, late-autumn/early-winter levels in 1990 throughout most of the principal aquifers had generally declined below any registered over the previous decade at least (see Table 10).

Considering lowland England as a whole, late autumn/early winter levels similar to those of 1989 and 1990 were recorded over wide areas in the 1976, 1973, 1964 and 1959 droughts. In central southern England levels generally remained depressed for substantially longer over the 1975/76 drought. At Rockley (near Swindon), for instance, the borehole remained dry throughout 1976 whereas in 1990 it was dry for less than three months. To the east, however, an obvious reversal in the relative severity

TABLE 10 THE 1990 DROUGHT - GROUNDWATER LEVELS IN DECEMBER

Borehole	Aquifer	NGR	First year of record	Av. Dec. level *	December 1990		No. of yrs with Dec. levels <1990	Lowest recorded level for any month prior to 1990
					Day	Level		
Dalton Holme (Humberside)	C. & U.G.	SE965453	1889	15.74	31	10.98	1	10.73
Washpit Farm (Norfolk)	"	TF814196	1950	43.48	04	41.31	1	41.24
The Holt (Hertfordshire)	"	TL169197	1964	86.89	06	85.81	3	83.90
Little Bucket (Kent)	"	TR123469	1971	64.05	31	57.63	0	56.77
Compton House (West Sussex)	"	SU775149	1894	39.65	28	27.96	1	27.64
Ashton Farm (Dorset)	"	SY662881	1977	66.88	11	63.20	1	67.62
New Red Lion (Lincolnshire)	L.L.	TF089303	1964	12.70	31	5.49	0	3.29
Ampney Crucis (Gloucestershire)	M.J.	SP060019	1958	101.97	10	97.38	0	97.86
Bussels (Devon)	P.T.S.	SX953987	1972	23.74	19	23.46	7	22.90
Alstonfield (Derbyshire)	C.B.	SK129555	1974	192.33	18	186.64	5	174.22

* Groundwater levels are in metres above Ordnance Datum.

C & U.G. Chalk and Upper Greensand
L.L. Lincolnshire Limestone
P.T.S. Permo-Triassic Sandstones
M.J. Middle Jurassic Limestone
C.B. Carboniferous Limestone

of the droughts may be detected as the meagre recharge over the winters of both 1988/89 and 1988/90 produced an exceptionally lengthy period of groundwater depletion. In a broad zone from the Chilterns to Lincolnshire groundwater levels in early winter 1990 stood below previously recorded minima. In the Midlands, levels in the Permo-Triassic sandstone aquifer, though less notably depressed, were generally at their lowest since the 1976 drought. Taking a longer historical context, it is clear that groundwater levels were persistently depressed during the 1940s and – on more limited evidence – the 1850s was also a decade characterised by low, to very low, groundwater levels.

Conclusion

1990 was a year of extraordinary spatial and temporal contrasts in the patterns of rainfall, river flow and aquifier recharge across most of the United Kingdom. Over the thirty or so years for which reasonably comprehensive surface water and groundwater monitoring networks have been in place, there is no close precedent to the extension of the range of recorded variation in rates of runoff and recharge in a single year. Whilst late winter runoff rates were exceptionally high in the wetter regions of Britain, sustained drought conditions impacted most heavily on those areas where the margin between water supply and demand is already relatively narrow. The inordinate recent seasonal contrasts in precipitation has highlighted the importance of its distribution in time as well as the overall amount, in causing hydrological stress. High evaporation rates and limited groundwater recharge – extending over a three-year period – served to emphasise the fragility of water resources in much of eastern England in the face of long term rainfall deficiencies. Ecological and amenity problems were exacerbated in certain, mostly lowland, areas where the impact of an evolving pattern of water use on natural flows has made headwaters especially vulnerable to drought conditions.

The exceptionally warm weather, parched soils, enhanced seasonality in rates of runoff and recharge and the threat posed to water resources in some areas, stimulated considerable public and scientific debate. Scientific and media interest was fuelled in particular by an apparent similarity between the conditions experienced in 1990 and an emerging consensus regarding the possible impact of climate change on hydrological systems and water resources. Given the capricious nature of the British climate, any attempt to draw general conclusions on the basis of a single remarkable year would clearly not be warranted. Nonetheless, the impact on natural systems, and on the community, of the weather patterns experienced over 1989–90 may provide important insights regarding our vulnerability to climate change.

On the evidence of historical data, the conditions experienced in 1989–90 may be expected only rarely. If as a consequence of climate change, such conditions recur with a significantly greater frequency in the future, the implications for the water industry and for the environment will be considerable. As research continues on a broad front to better assess the likely impact of global warming on rainfall patterns at the national scale, a continuing commitment to careful hydrometric monitoring will be essential to identify and quantify the effects on river flow and groundwater recharge throughout the UK. With relatively few rivers or aquifiers, especially in the lowlands, unaffected by man's activities the detection, unambiguously, of any climate-induced trends remains a considerable scientific challenge and underlines the importance of lengthy, quality controlled, records of rainfall, river flow and groundwater levels.

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