THE 1988/89 DROUGHT
A Hydrological Review

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The very dry and exceptionally warm late autumn and early winter in 1988 gave rise to considerable concern regarding the water resources outlook. In order to chart the progress of the developing drought and to assess regional variations in its intensity, the Department of the Environment requested that the Institute of Hydrology and the British Geological Survey undertake a hydrological monitoring programme and provide monthly reports dealing with rainfall, river flows and groundwater levels throughout England and Wales (coverage was subsequently extended to include Scotland). Hydrometric data for these reports are provided principally 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. Monthly Hydrological Summaries have been provided routinely since January 1989 and much of the material featured in the following article was assembled initially as part of the monitoring programme.

Over wide areas, the drought was well into its development phase by January 1989 and underwent a sharp amelioration at the end of the year. Unusually therefore, the calendar year provides a productive, if incomplete, timeframe within which to examine the drought's extent and severity. Consequently the 'Hydrological review of 1989' (pages 3 to 29) constitutes a valuable source of additional material; reference to various figures and tables in the review is made in the following article.

Hydrological Background

For its size, the UK experiences large regional variations in rainfall. The higher rainfall totals are associated with the maritime west, with the east – within the lee of the rain shadow from the Scottish Highlands, Pennines and Welsh mountains – becoming progressively drier with decreasing elevation. Annual average rainfalls vary from about 500 mm around the Thames estuary to more than 4000 mm in parts of the Scottish mountains, the Lake District and Snowdonia. Whilst in a global context UK rainfall may be considered to be evenly distributed, seasonal contrasts are appreciable, especially in the west where heavier falls are experienced through the winter, the wettest months being November to January. The contrasts are less strong in the drier areas, where August or November are typically the wettest months and spring the driest season.

A substantial proportion of the rainfall is accounted for by evaporative losses. Evaporation may occur directly from the soil, from open water surfaces, or as transpiration from plants. Knowledge of the soil moisture status and evapotranspiration rates are essential factors in any evaluation of water resources. Potential evaporation (PE) is the maximum evaporation which would occur from a continuous vegetative cover amply supplied with moisture. PE is a function of solar radiation, temperature, windspeed and humidity. It is most strongly influenced by radiation and temperature and the pattern is distinctly cyclical, with a peak normally in June or July. Typically, only 10–20 per cent of evaporation occurs during the winter half-year (October – March). In a normal year annual potential evaporation totals would be between 350 and 550 mm, and be greatest in the south and east of the country, especially in coastal areas where wind-speed is an important factor. A decrease is seen northwards and with increasing altitude; 350 mm being typical over the Scottish mountains. The ability of evapotranspiration to proceed at its potential rate is reduced as a result of drying soil conditions, the ability of vegetation to take up water and the measures plants take to restrict transpiration under such conditions. Thus in the absence of favourable soil moisture conditions, actual evaporation (AE) will fall below PE.

The change in evaporation rates through the year imposes a marked seasonality upon river flows, reservoir replenishment and groundwater recharge, each is concentrated in the winter and early spring. During the late spring and summer, the high evaporation demand causes a decline in river flows and leads to a progressive drying of the soil profile and the creation of what is termed a Soil Moisture Deficit (SMD); surface runoff and infiltration to aquifers is greatly reduced. When plant activity and evaporation slackens in the autumn, the higher rainfalls wet-up the soil profile and the cycle begins again.

It is arguable that Great Britain's geology and weather patterns are in harmony as regards the provision of water supply. Thus the older, more indurated lithologies characterising the west and north-west, with their relief and flashy runoff response from predominantly impermeable bedrock, are graced with substantial and regular amounts of precipitation from Atlantic frontal systems. The relief affords opportunities for natural or artificial impoundment to protect against supply difficulties during unusually long recessions. In eastern, south-eastern and southern areas, many of the more youthful lithologies are less tectonically disturbed, have been less well-cemented and show favourable water transmission characteristics; examples include the Jurassic and Cretaceous limestones and the Triassic, Cretaceous and Tertiary sandstones. These ensure more moderate river responses and a longer delay between seasonal aquifer recharge and baseflow to rivers, plus the opportunity for direct abstraction from aquifers, independent, as it were, of the obtaining meteorological conditions. The significantly lower rainfall in these areas may be separated into a winter component – providing aquifer recharge and insurance for the following summer via river and spring flow – and the summer half-year rainfall, the principal impact of which is in controlling the soil moisture conditions.

As a consequence of the geographical contrasts, regional susceptibility to drought varies considerably. In the west, very low rainfall for two or three months encourages steep recessions and leads to very low river flows; large rainfall deficiencies over longer periods of, say, five to seven months starting in the spring, puts stress upon reservoir systems (usually full at the end of the winter), excepting the largest. In the east, such deficiencies may normally be borne more easily (although the strains upon soil moisture conditions and plant growth may be severe). A substantial reduction in winter recharge can provoke more stress, leading to reduced baseflows during the following summer and a lower base to commence the next recharge cycle. Such a winter drought could also be a problem in the west but as winter rainfall depths are considerable even in a dry year, reservoirs are still likely to fill to acceptable levels which should provide supplies through all but severe spring and summer droughts.

The water industry, faced with the likely problems associated with the above drought scenarios, has developed a range of storage mechanisms and operational strategies to maintain levels of service linked to the probabilities of various drought intensities. Extending the role of reservoirs from direct supply impoundments to river regulators, the development of pumped storage schemes, increased networking of supply sources, cross-basin transfers, the integration of groundwater and surface water supply schemes and the evaluation of stand-by emergency sources together provide a flexible range of options to combat the effect of droughts. It follows therefore that the relationship between rainfall deficiencies, stress on water resources and impacts on the community is not a direct one.

The 1988/89 Drought in Summary

Following a wet winter and early spring in 1988, rainfall amounts were generally below average until the end of the year. A very wet July was limited in its hydrological effectiveness owing to high evaporative demand. The resources situation in the autumn was thus rather worse than the year's rainfall accumulation implied. Rainfall from August was modest through until the end of the year and, as a result, the anticipated strong seasonal increase in runoff and recharge rates failed to materialise. The winter of 1988/89 was exceptionally dry and by mid-February the English lowlands and the easternmost areas of Scotland were suffering from a notable drought. River flows were unseasonably low, groundwater levels had registered no appreciable seasonal upturns and the mild nature of the winter admitted record, or near record, evaporation rates creating large, persistent soil moisture deficits. A late-winter/early-spring interlude of substantial rainfall allowed reservoirs to fill, river flow rates to increase and some recharge of groundwater storage, whilst not satisfying all SMDs. Subsequently, the year to September was characterised by substantial hydrological recessions in most of the UK, a continuation of record evaporation levels and the widespread development of large SMDs. October rainfall lessened drought conditions in the west but deficiencies continued elsewhere into early December, when the conditions in many areas were those of severe drought. A distinct recovery generally took place in December but the water resources outlook in the east entering 1990 was fragile and the prospect of a second dry winter was a daunting one, especially in those areas predominantly dependent upon ground-water supplies.

Details of the development, extent and intensity of the 1988/89 drought are presented below within a hydrological framework.

Rainfall

The National Perspective

Whilst the seeds of the 1989 drought were sown in the late spring of 1988 in the lowlands, for England and Wales as a whole the rainfall deficiency beginning in August was more significant. By the middle of autumn, an incipient drought could be recognised but a general intensification occurred through the early winter. Table 6 shows four periods which best characterise the development of the 1988/9 drought. The ranking relates to the England and Wales rainfall series from 1766.

The November to January rainfall total was the lowest since 1879 and eclipsed the twentieth century record established during the 1933/34 drought. Particularly notable 1988/89 rainfall deficiencies may also be recognised over the seven and 13-month periods ending in November 1989. Within both timeframes – which broadly represent the duration over which the drought achieved its greatest intensity – the drought of 1920/21 may be seen as more

TABLE 6 ENGLAND AND WALES RAINFALL FOR SELECTED PERIODS

Rank	Aug.-Jan.		Nov.-Jan.		May-Nov.		Nov.-Nov.	
	mm	Year	mm	Year	mm	Year	mm	Year
1	325	1784/5	91	1879/80	344	1921	690	1920/1
2	328	1854/5	120	1857/8	355	1947	697	1853/4
3	343	1834/5	126	1829/30	371	**1989**	736	1780/1
4	345	1933/4	135	1780/1	385	1978	740	1933/4
5	349	1788/9	140	1788/9	391	1919	743	1802/3
6	364	1904/5	142	**1988/9**	395	1884	744	1857/5
7	371	1879/80	147	1812/3	399	1964	777	**1988/9**
8	376	1975/6	150	1783/4	402	1959	781	1784/5
9	377	1972/3	156	1933/4	406	1975	791	1892/3
10	379	**1988/9**	160	1834/5	410	1803	793	1863/4
For the Great Britain series beginning in 1869, the accumulations and rankings for1988/9 are:								
	572	35th	248	10th	487	9th	1076	27th

severe; over the longer duration the 1933/34 drought was also more intense. Considering intermediate and longer durations there are a substantial number of droughts which were more severe and/or of longer duration than the 1989 event. 1975/76 is outstanding in this regard but, taking as a yardstick the 1988/89 November to November accumulated rainfall total for England and Wales, there have been about 35 occasions this century on which lower 13-month rainfalls (starting in any month) have been recorded; the droughts of 1920/21, 1933/34, 1938, 1944, 1949 and 1955/56, as well as 1975/76, figure in this category.

A Regional View

Figures 8 and 9 show maps of rainfall, expressed as a percentage of the 1941–70 average, over the UK for November 1988 to November 1989 and May-November 1989. As with most droughts, a distinct regional dimension to the 1988/89 event is readily apparent. Certain common features may be recognised in both figures and also the annual percentage rainfall map (Figure 1 – see page 4). The largest areas of maximum rainfall deficiency are found along the eastern seaboard from the Wash to the Aberdeen coast; large deficiencies also typify the south-eastern corner from Great Yarmouth to Chesil Beach, the Eden valley in Cumbria and the Solway Firth, and the Welsh Borders around Herefordshire, all of which remained dry or relatively dry. In contrast, rainfalls were generally higher in Leicestershire and Northamptonshire, within a wetter band extending from the Bristol Channel to north Norfolk, with a

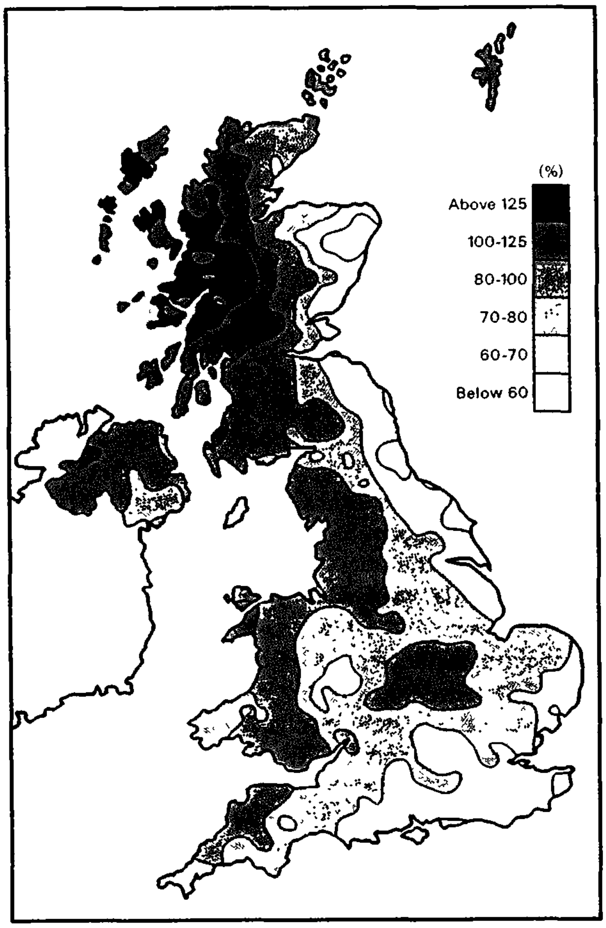

Figure 8. Rainfall from November 1988 to November1989 as a percentage of the thirteen-month (1941–70) mean.

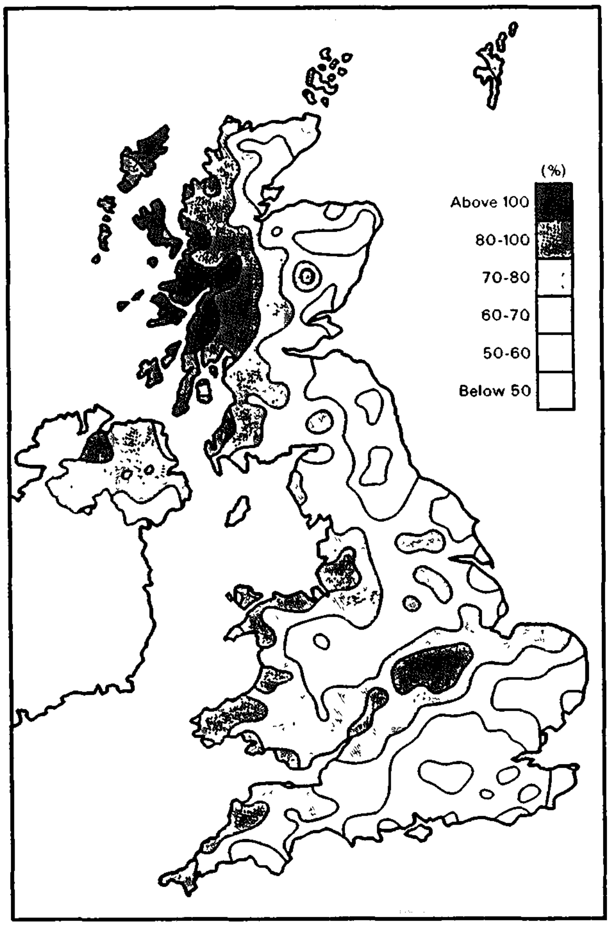

Figure 9. Rainfall from May to November 1989 as a percentage of the seven-month (1941–70) mean.

spur extending to the south-east Essex coast. Two-thirds of the UK recorded less than 70 per cent of average rainfall for the May to November period, with a further quarter below 80 per cent. The only area which was above average for all of the periods was western Scotland.

Table 7 provides national and regional rainfall statistics with estimates of return periods for a selection of durations corresponding to the periods of greatest drought severity and the wet period February to April 1989. In terms of rainfall anomalies over the widest area, the drought showed its greatest severity over the duration May-September 1989. Return period estimates are based on tables provided by the Meteorological Office; the tables reflect rainfall variability over the period 1911–70 only and assume a sensibly stable climate. The quoted return periods refer to the specified range of months only; the return period for *any* 'n' month sequence (as opposed to a particular sequence) would be about an order of magnitude less[1].

It is understandable that the extent of the deficiencies at the end of January provoked comparison with the droughts of 1933/4 and 1975/6 in central southern England. Although the greatest deficiencies over the November to January period were in these areas, it was notably dry along the whole of the eastern seaboard from the Grampian coast southwards. Western Scotland was experiencing very different conditions with a substantial steepening of the rainfall gradient towards the east.

The onset of heavy rainfall (from January in Scotland, mid-February in England and Wales) dispelled fears of a repeat of the 1975/6 winter half-year (the driest since 1879/80), although rainfall was not as heavy in the east, particularly the north-east of Scotland. The late spring saw a further transformation with the hot and dry conditions, which were a feature of the weather in May, persisting through the summer. Over England and Wales, the May to September period in 1989 ranks second driest, behind 1959, in the record from 1766; notably severe droughts could be recognised in both the northernmost and the Southern NRA regions (see Table 7).

From October through into December, rainfall was very much more abundant in the west of Britain than in the east. Rainfall accumulations of increasing rarity characterised many areas close to the eastern seaboard. Of particular note are the Northumbria NRA and the Tweed and North East RPB areas for the May to November period – each of the seven months falls were below average in these areas – and given the easterly rainfall gradient it is to be expected that even more extreme deficiencies would have developed in some low-lying coastal districts.

With the exception of parts of Scotland, the sustained, heavy rainfall which began in mid-December brought about a cessation of severe drought conditions; the dry weather continued in eastern Scotland through to the end of the year but rainfall in January and, especially, February effectively terminated the drought over all but a few extreme eastern districts of great Britain.

As regards the overall magnitude of the drought, the Southern NRA region registered the longest return periods for the widest range of durations; in England and Wales only the Northumbria region was comparable. In Scotland, the drought achieved its greatest severity over durations ending in December. Indeed, the Tweed and North East RPB areas recorded only two months above average rainfall in the period November 1988-December 1989, establishing a number of very large rainfall deficiencies associated with exceptionally long return periods, as presented below:

	Duration	Rainfall % lta	Return period years
North East RPB	Apr.89 – Dec 89	63	180 – 220
	May 89 – Dec.89	61	180 – 220
	Nov.88 – Dec 89	71	>200
Tweed RPB	Apr.89 – Dec.89	64	180 – 220

Catchment Rainfall

The rarities of the 1988/89 regional rainfall accumulations discussed above are supported by areal rainfall figures for catchments above gauging stations (see Table 8 – the location of most of rivers may be found on Figure 16). Of 102 catchments examined from Hydrometric Areas 9 through to 83 (see Frontispiece), with record lengths generally greater than 20 years, 72 recorded new November-January minima; 17 were of rank 2, 5 of rank 3 and 8 had less exceptional falls. For May-September, 54 recorded new minima and 24 ranked second. Given that the weight of a 'driest' ranking should be moderated by the length of record and that the stations selected are those which personify best the drought conditions during 1988/89, the uniformity of the 'driest' rankings for the four 'dry' accumulations provide evidence of a substantial drought embracing much of lowland England, with significant rainfall deficiencies extending north, west and north-east into Scotland. Of the regions not well represented by catchments in Table 8, the area from Leicestershire and Northamptonshire eastwards generally had more than 50 per cent of average rainfall but, for November 1988 to January 1989, catchment accumulations were, mostly, still the lowest on record.

The February to April period of heavy rain (January to March in Scotland) is seen to be amongst the wettest on record for these three months, with new maxima being recorded along the south coast

TABLE 7 NATIONAL AND REGIONAL RAINFALL ACCUMULATIONS FOR SELECTED DURATIONS WITH ESTIMATES OF RETURN PERIODS

		11/88 to 1/89	R.P. (yrs)	2/89 to 4/89	R.P. (yrs)	5/89 to 9/89	R.P. (yrs)	5/89 to 11/89	R.P. (yrs)	11/88 to 11/89	R.P. (yrs)
England and	mm	142		264		212		371		777	
Wales	%lta	52	20–50	145	20–50	57	20–50	67	20–50	77	20–50
NRA Regions											
North West	mm	261		373		297		526		1160	
	%lta	74	5–10	162	50–100	58	50–100	70	20–50	87	5–10
Northumbria	mm	158		206		189		295		659	
	%lta	63	10–20	119	2–5	49	>200	54	>200	68	180–200
Yorkshire	mm	129		226		192		314		669	
	%lta	54	20–50	131	5–10	55	50–100	62	50–100	73	30–70
Severn-Trent	mm	105		224		200		334		663	
	%lta	48	20–50	143	10–20	60	20–50	70	20	78	10–20
Anglian	mm	87		160		176		253		500	
	%lta	52	20–50	131	5–10	65	20	66	20–50	74	20–50
Thames	mm	78		206		162		264		548	
	%lta	39	50–100	148	10–20	54	30–70	60	30–70	71	30–70
Southern	mm	81		226		140		269		576	
	%lta	32	100–200	144	10–20	45	100–200	56	80–120	65	100–200
Wessex	mm	98		261		182		341		700	
	%lta	36	50–100	153	20	53	20–50	65	20–50	72	20–50
South West	mm	180		359		252		500		1039	
	%lta	45	20–50	147	20–50	58	20–50	73	10–20	78	10–20
Welsh	mm	230		413		293		582		1225	
	%lta	54	20–50	154	20–50	57	50–70	74	10–20	83	5–10

		11/88 to 1/89	R.P. (yrs)	1/89 to 4/89	R.P. (yrs)	5/89 to 9/89	R.P. (yrs)	5/89 to 11/89	R.P. (yrs)	11/88 to 11/89	R P (yrs)
Scotland	mm	454		633		458		705		1649	
	%lta	104	2–5	190	>>200	82	5–10	83	10	105	2–5
RPBs											
Highland	mm	664		907		563		900		2212	
	%lta	126	5–10	221	>>200	87	5–10	90	2–5	117	10–20
North East	mm	169		248		280		396		815	
	%lta	57	20–50	109	2–5	65	20–50	63	100–200	72	100–200
Tay	mm	334		526		353		540		1289	
	%lta	90	2–5	180	>200	69	10–20	72	20	94	2–5
Forth	mm	291		442		340		491		1135	
	%lta	92	2–5	180	>>200	71	10–20	71	20–50	93	2–5
Tweed	mm	189		281		277		375		822	
	%lta	66	10–20	128	5–10	63	20–50	59	180–220	74	50–100
Solway	mm	361		491		401		605		1405	
	%lta	83	2–5	152	20–50	70	10–20	70	20–50	89	5
Clyde	mm	538		723		571		888		1999	
	%lta	105	2–5	191	>>200	88	2–5	89	2–5	109	2–5

R.P. = Return Period lta = long term average

TABLE 8 CATCHMENT RAINFALL AND RUNOFF FOR SELECTED DURATIONS IN 1988/89

River/ Station name	Rainfall 11/88 to 1/89		Rainfall 2/89 to 4/89		Rainfall 5/89 to 9/89		Rainfall 11/88 to 11/89		Runoff 11/88 to 1/89		Runoff 2/89 to 4/89		Runoff 5/89 to 9/89		Runoff 11/88 to 11/89	
	mm %lta	rank /yrs	mm %lta	rank /yrs	mm %lta	rank /yrs	mm %lta	rank /yrs	mm %lta	rank /yrs	mm %lta	rank /yrs	mm %lta	rank /yrs	mm %lta	rank /yrs
Ugie at	106	1	139	12	218	2	560	1	105	3	71	2	58	3	259	2
Inverugie	43	/28	86	/29	70	/29	63	/28	58	/18	54	/19	57	/19	51	/18
Whiteadder Water at	120	3	163	11	234	2	587	2	89	5	78	3	43	1	223	2
Hutton Castle	53	/28	93	/29	69	/29	66	/28	63	/21	57	/20	47	/20	51	/20
Leven at	103	1	137	10	185	2	524	1	60	4	46	2	30	2	147	1
Leven Bridge	49	/30	86	/30	59	/30	63	/30	50	/30	44	/30	48	/29	43	/29
Foston Beck at	90	1	150	=14	158	1	488	1	35	4	30	3	45	4	121	2
Foston Mill	41	/30	94	/30	56	/30	61	/30	40	/28	21	/29	35	/29	30	/27
Derwent at	104	1	163	7	173	1	549	1	68	2	65	2	42	1	191	1
Buttercrambe	47	/17	94	/18	56	/18	65	/17	60	/17	54	/16	51	/16	52	/16
Trent at	144	1	241	17	231	1	803	=1	74	1	104	8	45	1	278	1
Stoke on Trent	56	/21	124	/21	67	/21	83	/21	49	/22	86	/20	43	/22	63	/20
Lud at	90	1	149	9	155	1	501	1	46	7	46	3	53	4	156	3
Louth	45	/21	91	/22	56	/22	66	/21	71	/22	43	/21	59	/21	55	/21
Waveney at	93	1	158	21	151	2	462	1	29	5	53	15	15	2	102	4
Needham Mill	55	/26	124	/26	61	/25	71	/25	44	/25	93	/26	52	/26	59	/25
Thames at	79	1	210	93	165	3	566	3	37	12	83	50	42	31	178	18
Kingston (nat.)	38	/106	140	/106	57	/106	72	/106	42	/107	95	/107	73	/107	66	/106
Mole at	76	1	238	26	141	1	567	1	23	1	116	16	15	2	163	1
Gatwick Airport	30	/28	133	/28	45	/28	63	/28	15	/29	108	/28	24	/28	42	/28
Great Stour at	89	1	209	22	156	1	575	1	42	1	69	5	48	2	177	1
Horton	39	/25	131	/25	55	/25	69	/25	41	/25	72	/24	59	/24	54	/22
Ouse at	83	1	237	26	126	1	574	1	33	1	117	9	51	6	218	2
Gold Bridge	30	/29	129	/29	40	/29	60	/29	21	/29	91	/29	67	/29	50	/27
Lymington at	79	1	273	29	149	1	653	1	37	1	118	18	13	1	188	2
Brockenhurst Park	29	/29	149	/29	51	/29	71	/29	29	/29	109	/29	23	/28	54	/28
Itchen at	81	1	261	30	155	1	638	1	79	1	105	4	125	3	352	2
Highbridge/Allbrook	30	/29	142	/31	50	/31	67	/28	64	/32	71	/31	77	/31	70	/31
Taw at	188	1	343	30	280	2	1059	4	142	2	238	22	39	4	557	3
Umberleigh	48	/31	137	/31	72	/31	83	/31	44	/32	120	/31	37	/31	71	/31
Brue at	112	1	272	22	205	1	730	1	78	2	171	20	38	4	308	2
Lovington	42	/25	140	/25	58	/25	75	/25	43	/26	121	/25	44	/25	64	/25
Severn at	136	3	282	=63	204	4	793	8	88	3	176	54	40	1	350	4
Bewdley	48	/69	147	/69	57	/69	78	/69	47	/69	130	/68	42	/69	69	/68
Teme at	97	1	226	=25	182	1	671	=1	64	2	144	19	27	1	259	3
Tenbury	38	/33	117	/33	55	/33	71	/33	39	/34	103	/33	38	/33	59	/33
Frome at	76	1	166	13	179	1	569	1	26	2	76	4	28	2	138	2
Yarkhill	37	/21	104	/21	62	/21	73	/21	25	/21	74	/20	55	/21	49	/20
Cynon at	288	2	645	32	317	1	1678	4	220	2	536	31	83	1	1139	7
Abercynon	45	/32	164	/32	54	/32	83	/32	41	/32	164	/31	33	/31	82	/30
Lune at	364	5	509	27	322	1	1497	6	330	4	446	27	90	1	1091	7
Caton	79	/25	169	/27	57	/27	91	/25	75	/26	167	/27	30	/27	87	/25
Eden at	255	2	383	25	198	1	1041	1	204	3	302	24	46	1	645	5
Temple Sowerby	67	/25	159	/25	47	/25	81	/25	67	/25	158	/25	28	/25	78	/25

into Devon and Cornwall and a common occurrence in Wales and the North-West.

Generally, examinations of drought intensity are conducted in terms of departures from the average rainfall or comparisons with corresponding historical rainfall totals. However, in actual rainfall amounts some exceptionally low seven and 13-month accumulations were recorded in 1988/89. At the catchment scale - and this may serve to exclude some of the lowest coastal accumulations - the driest areas over the May-September period were the Sussex Ouse (126 mm) and the Medway (134 mm); for November 1988 to November 1989 the lowest falls were from the Ore in Suffolk (447 mm) and the Beam in Essex (449 mm).

For individual raingauges, some exceptionally rare accumulations were reported; mention should be made of three records in the North-East examined by Wheeler[2]. Thus Durham University (record starts 1850), Whittle Dean Reservoir (1850) and Sunderland (1859) all recorded their lowest calendar year totals on record, Sunderland by a substantial margin. Shown below are the annual totals, previous lowest and return period estimates (adapted from Wheeler).

Station	1989 total mm	%lta	Prev. mm	Driest Year	Return Period in years
Durham	416	64	440	1959	100 - 150
Sunderland	353	55	417	1949	>>200
Whittle Dean	426	65	451	1959	>200

Evaporation and Soil Moisture Deficit

Evaporative Losses in 1989

Much of Great Britain registered annual mean temperatures for 1989 between 1 and 1.5 degrees Celsius greater than the 1951–80 average and the central England temperature series contains no warmer year in a 330-year record. High temperatures and a record number of sunshine hours encouraged high rates of evaporative loss in 1989. Figure 3 (page 9) shows the PE totals for a network of climatological stations throughout the UK. In south-western England some PE totals exceeded 750 mm; such totals are more typical of southern Europe. The MORECS (Meteorological Office Rainfall and Evaporation Calculation System)[3] model produces estimates of hydrological variables for a network of 40 km squares over Great Britain and uses a modified version of the Penman-Monteith equation to calculate PE for a range of surface covers. The model has been used retrospectively to produce a data series extending back to 1961. Examination of this dataset reveals that PE totals for 1989 were at record or near record levels over much of Britain. Annual PE totals generally exceeded those totals recorded in 1976. In Scotland and Wales, however, some 1989 PE totals fell short of those for 1984.

Figure 10 illustrates MORECS AE totals for 1989. AE is a conservative variable, generally constrained from very high values by the restrictions imposed by deficiencies in soil moisture and from very low ones by virtue of the limited period over which the soil moisture restrictions inhibit AE. Of particular interest is the effect the rainfall distribution in 1989 had upon AE estimates. The moist late-spring allowed evaporation close to the potential rate over wide areas, as significant shortfalls of AE to PE do not generally occur until SMDs exceed 60–70 mm. The rapid rise of SMDs through the late spring into the summer severely curtailed evaporation in the East and South-East and large shortfalls of AE below PE developed, the highest since 1976. The annual shortfall of AE below PE is illustrated in Figure 11; shortfalls were commonly in excess of 140 mm throughout lowland England, the north-eastern seaboard and in the South-West. In the MORECS square encompassing part of the River Itchen catchment in Hampshire, a shortfall of over 260 mm was recorded, some 220 mm greater than that recorded during 1988 - another very warm year.

Very high AE totals were recorded in the west in 1989 and generally totals decreased south-eastwards, although much of the south and north-east of Britain recorded values above 90 per cent of the 1961–88 average. The apparent inconsistency between the high percentage of average AE and the high summer shortfalls of AE below PE may be explained by the well above average evaporation rates in the winter of 1988/9 and the autumn and winter of 1989/90. For 1989 as a whole, variations in AE totals were subdued in comparison with 1976, as then the drier winter and spring allowed AE shortfalls to develop earlier. For comparison, 1989 AE totals were in the range 450–500 mm; those in 1976, 300–550 mm.

Evaporation and the Development of SMDs 1988/89

During the winter period - October 1988 to March 1989 - exceptionally mild temperatures gave rise to record or near record PE totals throughout much of Britain. PE totals for the winter period were in excess of 20 per cent of the average annual total. AE totals were similarly high, as water availability was such as to allow evaporation at, or close to, the potential rate.

Figure 4 (see page 10) shows the development of the shortfall of AE below PE throughout the year for 5 MORECS squares, compared with the more modest conditions over 1985 to 1988.

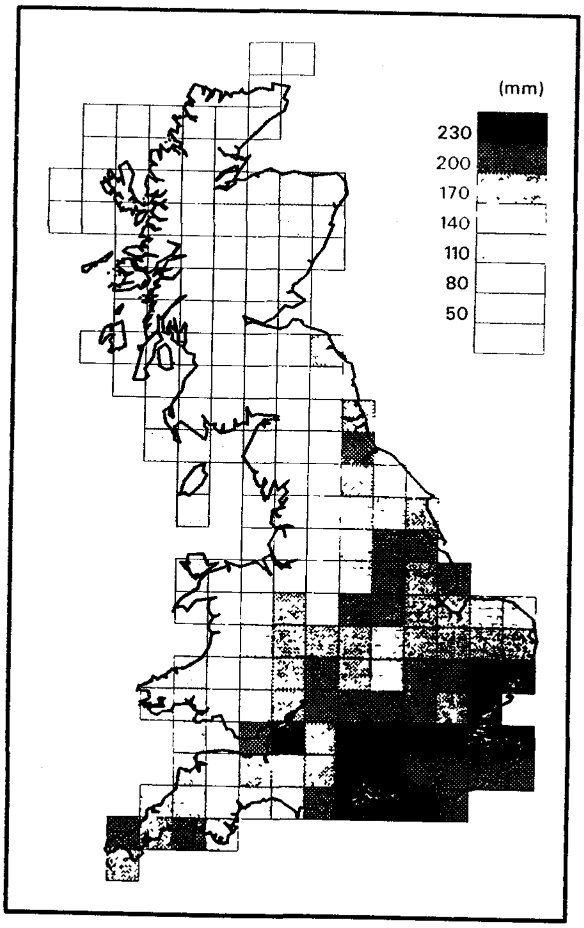

Figure 10. Actual evaporation (for grass) in mm for 1989.

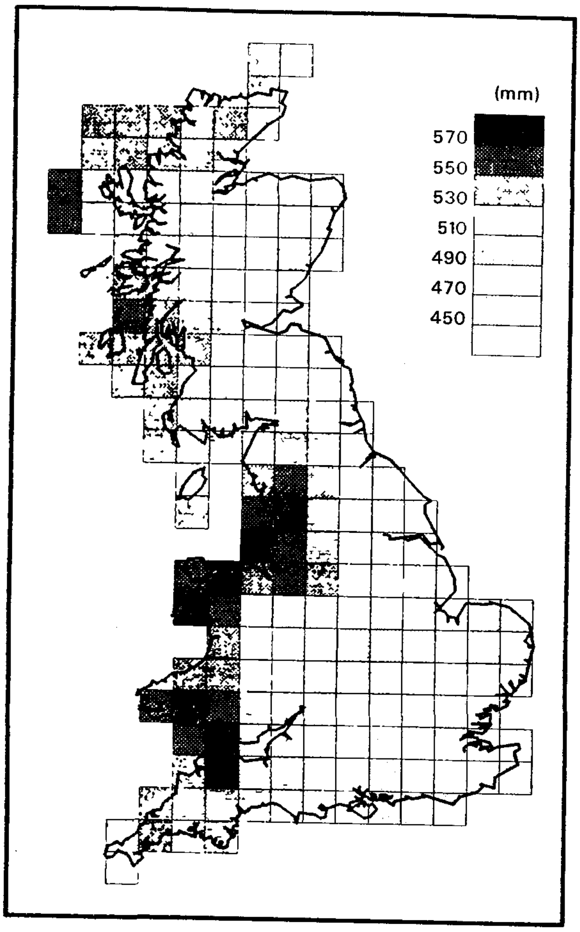

Figure 11. Shortfall (in mm) of actual evaporation (for grass) relative to potential evaporation for 1989.

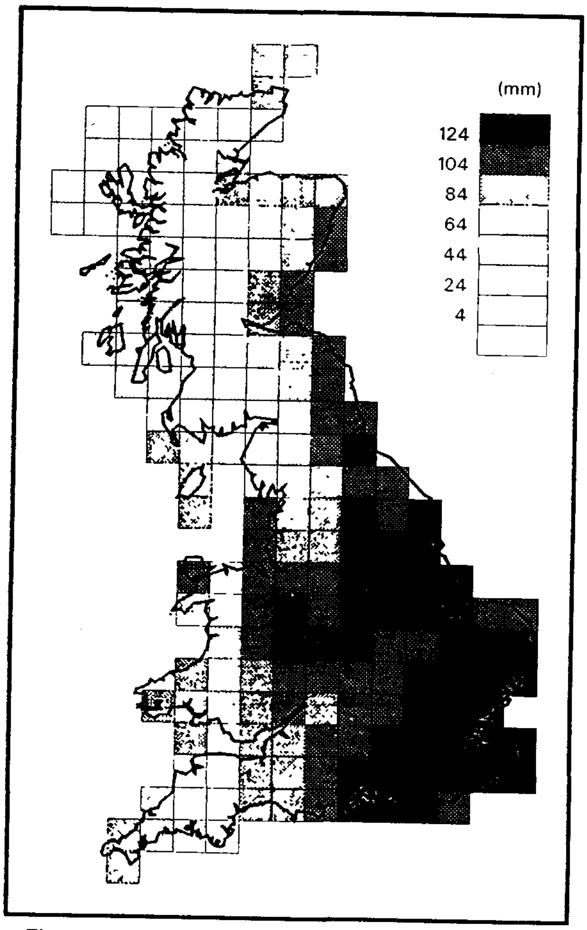

Figure 12. Soil moisture deficits for grass at the end of September 1989.

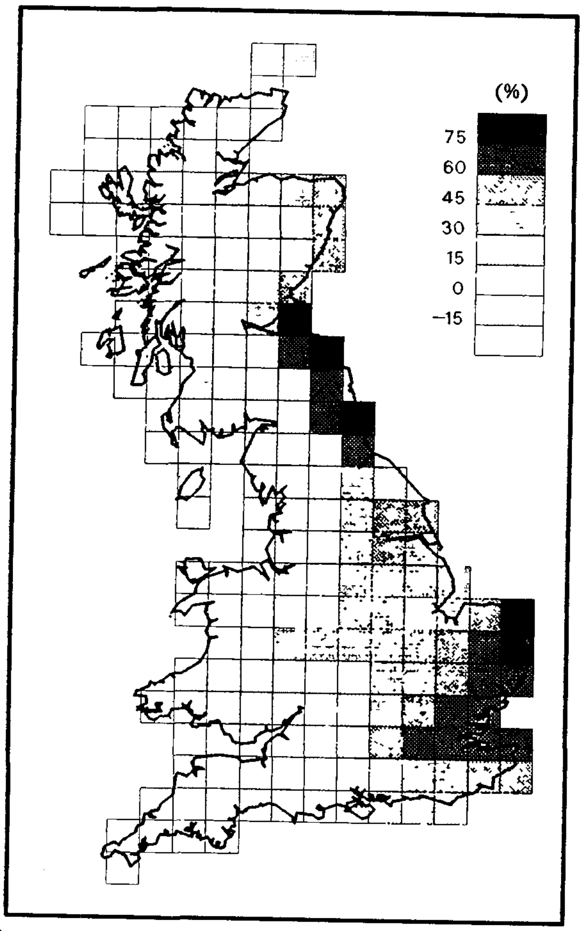

Figure 13. Soil moisture deficits at the end of November 1989 expressed as a percentage of the corresponding long term average.

Data Source: MORECS.

In the north-west of England and south-western Scotland (see Square 55 in Figure 4) the shortfall was high compared with the previous four years but fell below that of 1984. The remaining squares all demonstrate significantly greater shortfalls persisting late into the year.

The development of SMDs is also illustrated in Figure 4 (see page 10), again using standard MORECS data. Square 108, covering the Lower Trent valley, exhibited persistently high SMDs throughout the winter, a characteristic shared with other areas including Humberside, Lincolnshire, the Wash and the Lower Thames valley. The January-end deficit of 66 mm for grass (the SMD values presented here all relate to a grass cover – higher deficits would apply for a forest cover) was the highest estimated since the start of the record (1961); the previous maximum was 39 mm in January 1976. Despite a relatively wet spring significant SMDs existed throughout the year in some eastern locations and exceptionally high deficits were registered during the summer and autumn. In Kent (MORECS square 174), SMD remained above average for the whole year, with deficits above 100 mm being attained from June to September. Adjacent to the Thames estuary values exceeded 100 mm from May to November. Further north in Northumberland (MORECS square 66) SMDs reached above 110 mm for two months; previously only single months in a year had registered over 100mm (1976 and 1984). In the west of the country (MORECS square 134), a new maximum SMD value of 120 mm was recorded in August.

Over the summer months, June to August, calculated SMDs for most of southern Britain and the eastern seaboard exceeded the 1961 to 1988 mean by some 20–80 mm. In western Scotland and north-western England in particular, rainfall during June, and again in August, restrained the development of unusually large deficits. In southern England the maximum deficit of 125 mm (for the grass model) was reached as early as July. By the end of August, 48 of the 190 MORECS squares were registering such maxima. The areal extent of SMD maxima for grass, aggregated irrespective of the time of year, were almost identical for both 1989 and 1976, the pattern being similar to that illustrated on Figure 12 but extending westwards towards the Welsh Borders and south-westwards to Exeter. In August 1976, however, deficits considerably greater than 125 mm were calculated for ground cover other than grass and, in soil moisture terms, the drought was substantially more severe than in 1989. However, heavy rain early in the autumn of 1976 led to a brisk decline in SMDs whereas in 1989 soils remained very dry and the extent of the area at maximum deficit by the end of September was remarkable.

During October SMDs were reduced – substantially so in the west, where deficits were eliminated in some parts by the end of the month. However, as a result of anticyclonic conditions during November, SMDs began to build once more and achieved a very unusual magnitude entering the 1989/90 winter especially in the east. Figure 13 illustrates actual deficits for November expressed as differences from the 1961–88 average. The largest difference may be recognised in East Anglia and on the north-eastern seaboard, with a general reduction in anomalies moving westwards. Whilst a sharp decline in deficits occurred overall in December, many deficits remained above the December average in the east of Britain at year-end. In the MORECS square 66 (associated with the River Leven catchment), a December SMD value some 40 mm above the long-term average was calculated.

The atypically high temperature and evaporation levels in 1989 were instrumental in reinforcing a substantial rainfall deficiency. The associated growth and decay of SMDs followed an unusual pattern with very high deficits – relative to the seasonal average – both at the start and near the end of the year.

Runoff

Runoff from Great Britain as a whole was not significantly below average in 1989, principally reflecting the abundant runoff from the Scottish Highlands throughout a large part of the year. For England and Wales however, the annual runoff total was easily the lowest since 1976. Whilst spatial contrasts were subdued compared with Scotland, clear regional differences may be identified in Figure 5 (page 13), confirmed by the annual runoff section of Table 4 (page 15). The range of catchments recording new minimum annual runoff totals serves to delineate the zone of severe runoff deficiency quite effectively: along much of the eastern seaboard and the south coast to Dorset. Catchments in eastern Scotland and Northumberland south to Yorkshire feature prominently in Table 4, often displaying shortfalls of 40 per cent and above between the 1989 annual runoff totals and previous minima.

It is fortuitous for annual runoff totals to provide more than a general guide to a drought's intensity but the eight hydrographs for 1989 in Figure 14 enable the main features of the drought to be identified; the selected stations reflect the more seriously affected areas (the fainter envelopes are the daily maxima and minima from the previous record). The notable features are: the depressed runoff levels through into February; the higher proportional runoff in the South and West, compared with the East, as evidenced by the scale of the flow upturns during the spring; the duration within the year when the flows

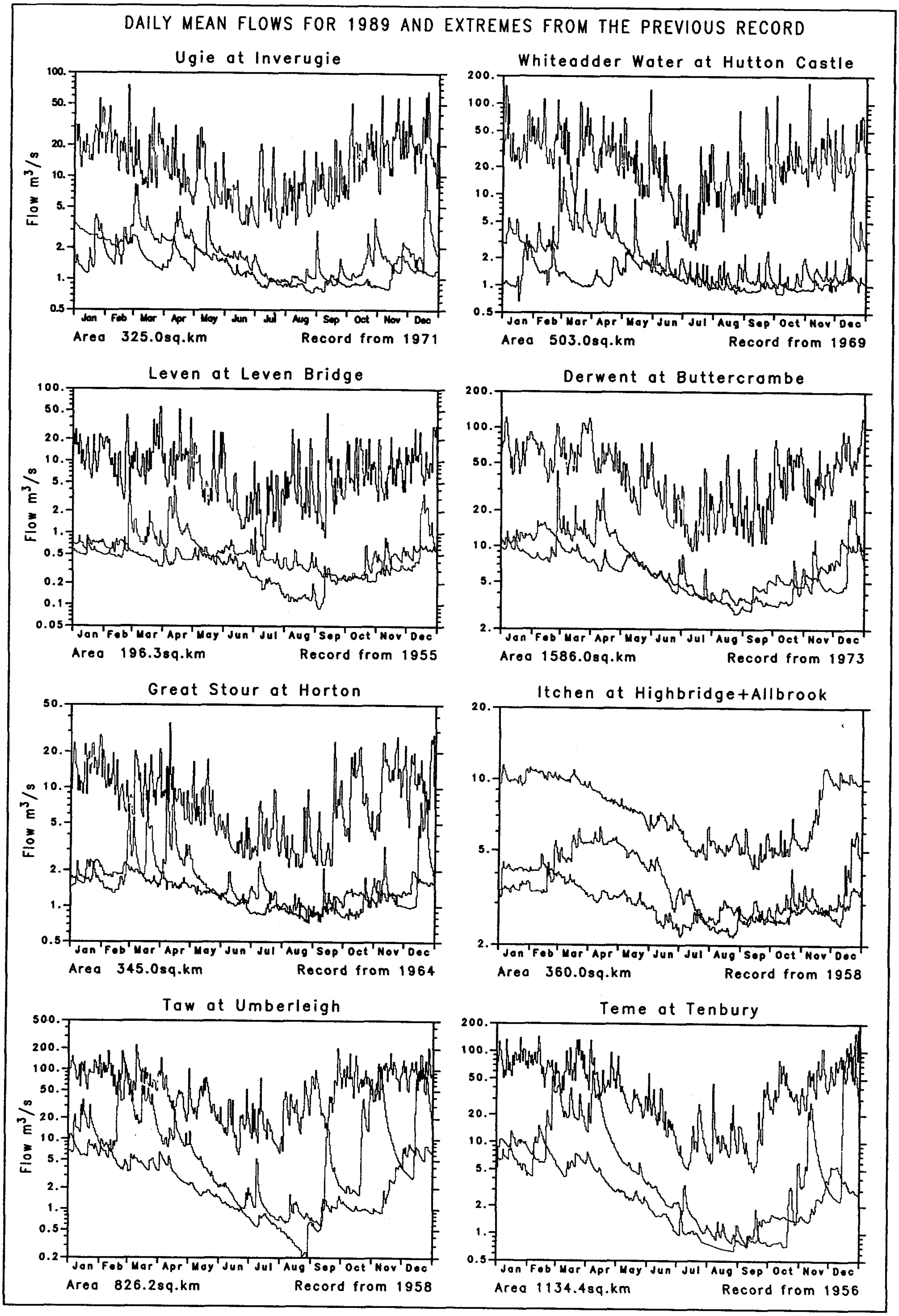

Figure 14. 1989 River flow hydrographs.

were around the minimum recorded; the recovery in the west in September and October; the singular November-December recession, followed by the sharp end of year upturn*.

In some catchments, the onset of below average flow conditions was established early in 1988 and continued substantially unaltered through to the end of 1989; thus the Medway recorded only two monthly flows above average during February 1988 to December 1989 and the Itchen registered 17 months below average from August 1988. The depressed flows at the start and the end of the year caused a loss of riparian amenity as headwaters in baseflow-fed streams contracted. As an example of an affected bourne stream, the Lavant, gauged at Graylingwell (Hampshire), near the Chilgrove borehole, (see also Figure 15) recorded its highest ever flow in February 1988 but was dry by August and remained dry through to the end of 1989, the longest dry sequence since 1973.

Regional and Catchment Runoff

Monthly runoff minima were superseded in 1989 over a wide area, notably in January, July, September and November; some new absolute minima were established (see Table 4, page 15). November commonly saw lowered monthly minima in some eastern Scottish and north-eastern English catchments and a number of annual minimum daily flows were recorded in November. A few were registered in December but, from the second week, some remarkable river flow recoveries occurred – the Wye in Buckingshamshire and the Quinn in Hertfordshire, for example, recorded their maximum daily flow of the year within 10 days of recording their minimum! Such transformations are rare in the UK and in southern England were somewhat reminiscent of the sharp upturn in runoff rates associated with the record November rainfalls which terminated the 1929 drought.

Table 8 contains runoff accumulations for selected durations and their rank within the period of record (alongside the corresponding rainfall data). In the South and the East, both responsive and baseflow-fed rivers registered record low flow accumulations for the three months beginning in November 1988, the responsive streams owing to the paucity of rainfall and the baseflow streams because of a combination of a long groundwater recession from the spring of 1988 and the lack of winter recharge.

* The use of logarithmic axes requires that caution is necessary when visually interpreting the varying flow ranges for the stations illustrated. The maximum flow on the Itchen, for instance, is greater than the least by a factor of five; for the Taw the factor is closer to 2000.

In relatively few cases was the high rainfall of the February to April period translated into equivalently ranked runoff. This could be anticipated given the unusually dry antecedent conditions for early spring rainfall. Runoff accumulations encompassed a broad range from being among the driest on record (east Scottish coast, the North-East and baseflow rivers in much of lowland England) to being well within the normal range – wide areas of the Midlands, East Anglia and the South West. Only in those areas which tapped the wetter west did rivers record amongst their highest February to April flows. These included the Tay and the Tweed in eastern Scotland and rivers in western Wales, Lancashire and Cumbria.

The most exceptional accumulations for May-September 1989 were in the North-East, the Welsh Borders and north western England. Runoff from East Anglia and the East Midlands was below average but generally unremarkable. In southern and eastern Britain, the preponderance of second ranked entries in Table 8 is associated with the dominant influence of the 1976 drought on low flow records; even though 1976 saw heavy rainfall in September, it was not effective enough to generate a widespread runoff recovery. A comparable situation obtained in the east from Yorkshire through to the Grampian region, where many accumulations ranked behind the droughts of 1972/73 and 1964/65.

The combined effects of the very wet early spring and wet autumn in 1989 is noticeable in the 13-month accumulations in the north-west of England, moderating the often exceptionally dry early winter and summer conditions. Elsewhere, rather rarer 13-month totals were observed; East Anglia and the East Midlands recorded substantially below average totals. Many catchments close to the eastern seaboard and along the south coast registered their lowest, or second lowest, November-November runoff total; over half of more than 100 catchments examined were of rank 1 or 2.

As the catchments featured in the tables and hydrographs were chosen as being representative of their regions, some remarkable statistics have not been featured. The upper Leven – a tributary of the Tees – gauged at Easby since 1971, spent 180 days of 1989 below previous minimum daily values and recorded six new monthly minima in the process. The River Seven which drains from the North York Moors, had a 1989 mean flow less than half that of the previous minimum. The Foston Beck, on the Yorkshire Chalk, spent from April 1988 through to November 1989 in recession, recording new monthly minima for the last three months of 1989. The upper Trent at Stoke recorded new minima for a whole range of accumulations, including the calendar year 1989, and longer periods, for example from April 1988 to November 1989.

Low Flow Frequency Analysis

Whilst the tabulated rankings give a rough guide to the rarity of accumulations, it is possible to examine frequencies of occurrence of low flow periods within a more rigorous statistical framework. The measurement of low river flows is subject to many influences which may limit its accuracy, from the hydrometric aspects, such as imprecise stage-discharge relations owing to weed growth and/or insensitive controls, to the effects of artificial influences on the flow regime. It is unfortunate that it is not easy to quantify the latter effects for particular flow sequences and that more data sets are not available for rivers where the net impact of abstractions and discharges is minimal.

Frequencies of occurrence for low flow durations may be derived using the methodology recommended in the Low Flow Studies[4]. The estimation procedure needs to be approached with caution owing to: the accuracy of low flow measurements (see above); variation in record quality over time; and the inadequacies of short record lengths (and the associated need for uncertain extrapolation), the accomodation of outliers and the omission of historical droughts. Table 9 provides a guide to the likely frequency of river flows in a selection of catchments for a number of durations from 30 to 365 days. The method has the benefit of choosing the lowest sequences from the whole (or selected portion) of the record regardless of arbitrary month boundaries but sequences have to begin and end within the calendar year.

The Scottish and north-eastern English catchments show increasing return periods with longer durations, a feature common to the rainfall pattern, whilst in the west of England and in Wales the highest return periods are associated with the medium durations; the decrease in rarity for the long durations is a reflection of the wetter autumn in these areas. There is relatively little difference in the return periods estimates across the durations between the more responsive and the baseflow dominated catchments.

TABLE 9 LOW FLOW FREQUENCY ANALYSIS: RANKING OF VARIOUS LOW FLOW DURATIONS IN 1989 AND ESTIMATES OF ASSOCIATED RETURN PERIODS

Station	Duration (Days)															
Number	30		60		120		150		180		210		365		Record	Base Flow
	Rank	R.P.	Rank	R.P.	Rank	R.P.	Rank	R.P.	Rank	R.P.	Rank	R.P.	Rank	R.P.	Length	Index
10002	4	5	3	5–10	3	5–10	3	5–10	2	10	2	10–25	2	50–100	18	0.60
21022	4	5	4	5	3	5–10	2	10–25	2	10–25	1	10–25	2	10–25	20	0.52
25004	2	25–50	2	10–25	1	25–50	1	25–50	1	10–25	1	25	1	50	29	0.53
25005	3	10–25	2	25	3	10–25	2	10–25	2	10–25	2	10–25	1	50	29	0.43
26003	2	25–50	2	25–50	2	25–50	2	25–50	2	25–50	2	25–50	2	50	27	0.95
27041	2	10–25	2	25–50	1	25–50	1	25–50	1	25–50	1	25–50	1	25–50	16	0.68
28040	1	25–50	1	50–100	1	25–50	1	50	=1	25–50	2	10–25	1	10–25	21	0.48
29003	3	10	3	5–10	2	10	2	10–25	2	10	2	10	3	10–25	21	0.90
34006	4	5–10	3	5–10	2	10–25	1	25–50	1	25	1	50	1	50	26	0.48
39001 nat.#	2	5–10	2	5–10	2	10–25	2	10–25	2	25	2	25–50	2	5–10	39	0.64
39054	2	10	3	10	3	10–25	3	25	2	10–25	2	25	2	10–25	28	0.25
40011	3	10–25	3	25–50	2	25	1	25–50	1	25–50	1	25–50	2	25–50	24	0.69
42003	3	10–25	3	25–50	3	25	2	25–50	2	25	2	25	4	10–25	28	0.36
42010	2	25	2	25–50	2	25–50	2	50	2	25–50	3	50	3	50	31	0.97
46003	3	5–10	3	10–25	4	10–25	4	5–10	=5	10–10	6	5–10	5	5–10	31	0.52
50001	5	10	3	10–25	3	10	4	10	6	10	6	5–10	8	2–5	31	0.42
52010	2	5–10	2	10–25	2	10	2	10	2	5–10	1	25	2	10–25	25	0.47
54008	2	10–25	2	25–50	2	25–50	2	25	1	10–25	3	10–25	7	10–25	33	0.57
55018	2	10–25	2	25	2	25	2	25–50	=1	25–50	2	25–50	4	5–10	20	0.50
57004	4	5–10	3	10–25	1	25	1	50	1	25–50	6	10	14	2	30	0.42
72004	3	10	7	5	3	10–25	2	10–25	2	10–25	2	10–25	8	5	27	0.32
76005	2	25–50	1	25–50	1	25–50	1	50	1	25–50	2	25	5	5–10	25	0.37

R.P. = Return Period

Flow record from 1951 (when major structural improvement to the gauging weir was completed) only used in the analysis.

The featured stations monitor flows on the following rivers:
10002 - Ugie; 21022 - Whiteadder; 25004 - Skerne; 25005 - Leven; 26003 - Foston Beck; 27041 - Derwent (Yorks); 28040 - Trent; 29003 - Lud; 34006 - Waveney; 39001 - Thames; 39054 - Mole; 40011 - Great Stour (Kent); 42003 - Lymington; 42010 - Itchen; 46003 - Dart; 50001 - Taw; 52010 - Brue; 54008 - Teme; 55018 - Frome (Herefordshire); 57004 - Cynon; 72004 - Lune; 76005 - Eden.

Historical Comparisons

Because of the effect of natural and artificial storages in individual catchments, the frequencies of the low flow events for comparable periods may differ substantially from those derived from rainfall data. A major difficulty in providing a satisfactory historical perspective for the recent runoff variability is the dearth of long flows records to provide an adequate geographical coverage; the average record length on the Surface Water Archive is about 22 years. The flow frequency estimation procedure discussed above generally allows valid inter-drought comparisons at the shorter durations. As they increase beyond six months however, the procedure begins to favour drought profiles which fall within a calendar year and address less adequately those droughts which extend over periods substantially greater than one year. For the stations featured in Table 9, the drought of 1976 is widely ranked first for durations of 150 days and less and is still the dominant drought at 180 days, particularly in central and southern England. Return periods for 1976 flows are characteristically 25 to 50 years and above for these durations; for the Itchen and Thames, all durations bar the 365-day have return periods in excess of 100 years. From the Yorkshire coast northwards, 1976 is supplanted by 1972, 1973 and 1964 as the dominant event(s) at the shorter durations, although return periods are generally less than 100 years. In these areas at the longer durations, the 1989 data indicate a drought of notable severity.

Ranking runoff accumulations from lengthy station records provides a means of generally assessing the relative severity of historical drought events. Table 10 features three catchments, two representing the most affected areas in the east and one in the west. The River Dee record demonstrates that 1988/89 was one of the most significant droughts to have affected eastern Scotland. The effect of two exceptionally dry autumn periods is evident in the 13-month ranking for the Foston Beck and the primacy of the 1988/89 runoff accumulations for the Kent Stour serves to emphasise both the regional intensity and the persistence of the hydrological drought. As with the Foston Beck, a less extreme picture may have emerged had flow data been available for the 1959 drought and the sequence of very dry episodes in the 1940s.

Compared with previous droughts, 1988/89 over its widest compass is the most severe since 1975/76. As this compass is close to a calendar year (November 1988 to mid-December 1989), it is interesting to note that whilst runoff for 1989 in England and Wales is substantially lower than for the preceding 12 years, runoff in 1976, 1975 and 1973 (especially) was less than in 1989; the 1971 total was closely equivalent. Incorporation of the 1975/76, 1984 and 1988/89 data into the flow frequency analyses has shortened some of the return periods ascribed to the 1975/76 event, but for extent, severity and duration the 1975/76 event remains the dominant drought event in central and southern England. In the north-east of Great Britain, however, the 1988/89 drought should be considered as one of the most severe this century.

TABLE 10 MINIMUM RUNOFF TOTALS FOR SELECTED GAUGING STATIONS

DEE AT WOODEND STARTS: 1929		FOSTON BECK AT FOSTON MILL STARTS:1959		GREAT STOUR AT HORTON STARTS: 1964	
November 1988 - January 1989					
mm	year	mm	year	mm	year
168	1958/59	31	1964/65	42	**1988/89**
177	1975/76	32	1973/74	55	1971/72
178	1964/65	34	1972/73	59	1973/74
189	1969/70	35	**1988/89**	63	1972/73
195	1972/73	40	1962/63	73	1980/81
199	**1988/89**	43	1977/78	77	1978/79
May - December 1989		May - November 1989			
mm	year	mm	year	mm	year
279	**1989**	41	1973	68	**1989**
314	1937	56	**1989**	84	1972
324	1955	77	1976	85	1973
326	1971	85	1965	93	1985
340	1975	116	1971	99	1984
353	1933	123	1982	105	1965
November 1988 - December 1989		November 1988 - November 1989			
mm	year	mm	year	mm	year
685	1972/73	101	**1988/89**	178	**1988/89**
735	**1988/89**	121	1964/65	195	1972/73
755	1970/71	139	1962/63	213	1971/72
763	1963/64	282	1961/62	251	1975/76
827	1948/49	286	1970/71	264	1983/84
849	1964/65	291	1971/72	277	1980/81

A remarkable feature of the 1988/89 runoff pattern is the two successive autumns where runoff rates have declined to very low levels. The protracted delays in the seasonal recovery in runoff rates have implications both for river amenity and for water resources.

Groundwater

In relation to groundwater resources the most salient feature of the 1989 drought was the dramatic contrast between standing water levels at the end-of-year and the near-record levels obtaining, over wide areas, during the spring of 1988. The singular magnitude of storage depletion over this period is illustrated in Table 11 which includes an assessment of the overall 1988/89 range of groundwater levels for selected boreholes together with its rank relative to other two-year declines in the water-table (from the peak of one recharge cycle to the minimum of the next cycle, typically 20–22 months). In most of the listed wells there is no precedent for the recent transformation. Equally, recharge over the 1988/89 winter half-year was notably modest and inordinately delayed. The delay was beneficial in the sense that groundwater levels in April were, generally, rising at a time when the spring recessions are normally well established. As a consequence water-tables were only moderately depressed through the summer but the fragility of the groundwater outlook through 1989 may be gauged by considering the implications of an even more protracted delay before rainfall rates increased in mid-February. A further delay of six to eight weeks would have robbed the rainfall of much of its hydrological effectiveness (as evaporation rates climbed) and made for a substantially more sombre resources prognosis.

Whilst a distinct seasonal cycle is the most pronounced feature of groundwater level time series, many display a considerable degree of persistence also – levels commonly remaining above, or below, the seasonal mean for extended periods. Annual recharge amounts are, clearly, the critical factor in determining water-table height (although pumping effects may be influential locally and regionally) but the level from which the winter recovery needs to be generated, together with the steepness and duration of the seasonal recessions are very important also. Natural groundwater base levels – below which no outflow via springs and streams will occur – may, in some aquifers, only be approached after recessions extending well beyond the normal six to eight months between recharge episodes.

Once groundwater levels become exceptionally depressed, even above average recharge may well not restore water-tables to their normal spring level. Thus, the very limited recharge experienced in 1989 needs to be considered in the perspective of the notably low levels registered in the autumn and early winter of 1988/89 and the sustained recessions following the cessation of infiltration in the spring. In western areas, where heavy October rainfall signalled the onset of the 1989/90 recharge season, the minimum 1989 groundwater levels were generally well within the normal range. By contrast, close to the eastern seaboard late-1989 levels approached the lowest on record and in some localities, from Kent to Northumberland, the December levels were unprecedented.

TABLE 11 1988/89 BOREHOLE LEVEL RECOVERIES AND 1989 MINIMA COMPARED WITH THE PERIOD OF RECORD

Borehole/ aquifer	First year of record	Average Recovery (m)	1988/9 recovery (% of average)	Long term minimum (m) and date	1989 Minimum (m) and date	Years with minimum <1989 min.	Range (m) 1988-89	Rank of 1988/89 depletion*
Dalton Holme Chalk and UGS	1889	7.10	40	10.73 14/12/89	10.73 14/12	None	11	1
Little Brocklesby Chalk and UGS	1926	7.57	35	4.56 24/09/76	5.77 15/12	1 (1976)	13	6
Washpit Farm Chalk and UGS	1950	2.95	8	41.24 24/11/78	42.13 04/12	7	7.9	1
Rockley Chalk and UGS	1933	10.91	69	Dry	Dry	–	14	5
Compton House Chalk and UGS	1894	21.76	64	27.62 14/10/76	28.30 20/12	3	34	1
Little Bucket Farm Chalk and UGS	1971	21.09	20	56.77 01/11/76	57.81 06/12	2	30	1
Lime Kiln Way Chalk and UGS	1969	0.92	46	124.09 01/10/76	124.27 09/12	1 (1976)	1.1	4
New Red Lion Lincolnshire Limestone	1964	9.21	50	3.29 24/08/76	7.20 18/12	1 (1976)	12.7	3
Llanfair D.C. Permo-Triassic sandstone	1972	0.74	53	78.85 01/09/76	79.25 23/10	1 (1976)	1.4	1
Bussels No. 7A Permo-Triassic sandstone	1971	1.17	36	22.90 31/08/76	23.19 14/10	3	1.4	4

UGS=Upper Greensand

* 1=min.