THE 1995 DROUGHT – a water resources review in the context of the recent hydrological instability

T. J. MARSH
Institute of Hydrology

Extreme rainfall deficiencies and very high temperatures throughout the spring and summer of 1995 produced considerable stress on water supplies and river systems. The drought attracted substantial public, political and scientific interest fuelled, in part, by speculation regarding the likely impact of climate change on the UK. In this article the drought's extent and severity is examined in a water resources perspective – and within the context of the very unusual climatic conditions which have characterised much of the last 20 years.

Introduction

Taken together, the two decades ending in 1995 have seen both an exaggeration in the north-west to south-east rainfall gradient across the British Isles and a more distinct partitioning of annual rainfall totals between the winter and summer periods[1]. In addition, most of the recent past has been remarkably mild encouraging exceptionally high rates of evaporation. These tendencies, which show a broad consistency with a number of favoured climate change scenarios, have raised questions regarding the resilience of existing water resource management strategies and the sensitivity of aquatic habitats to relatively modest changes in runoff patterns.

The United Kingdom's continuing vulnerability to hitherto unusual weather patterns has been underlined by a number of notable drought episodes over the 1988–94 period[2,3]. They varied in spatial extent and severity but none matched the intensity of the 1975/76 drought[4]. The relatively modest impact of this extreme rainfall deficiency on water consumers and the aquatic environment provided a vindication of existing water management strategies. An intense but relatively short-lived drought in the spring and summer of 1984[5] provided a further test of water management arrangements especially in northern and western Britain but generally water resources remained healthy over the ensuing 12 years. However, the privatisation of the water industry in England and Wales in 1989 coincided with the early stages of a notably volatile period for weather patterns. Sustained periods of very wet or very dry conditions characterised most regions of the UK; these were associated with an extension in the recorded range of river flow and aquifer recharge rates in a number of regions[3]. When considered in the context of historical rainfall and temperature data, the recent drought episodes may legitimately be considered as rare events. However, the clustering of rainfall deficiencies, over a range of timeframes, and the persistently high temperatures over the last 20 years, raises important questions regarding the ability of historical hydrometric data to provide an appropriate basis for the design and development of improved water management strategies. Such problems, which assume a particular significance given the increasing evidence of global warming, were brought into sharp focus during a remarkably dry five-month spell beginning in the early spring of 1995.

Overture to the 1995 Drought

The 10-year period ending in 1986 was, at the time, the wettest on record for the UK as a whole and, for most regions, mild wet conditions continued through the winter of 1987/88. Following a wet July in 1988, modest rainfall deficiencies developed through the autumn which heralded widespread and severe drought conditions in 1989 and 1990[3]. Exceptionally high temperatures were a major contributory factor in both years. Each year ranks amongst the four warmest in the 337-year Central England Temperature series[6]. The following two years were less outstanding but in the English lowlands the drought persisted (especially in groundwater terms) into the autumn of 1992.

By late August 1992 soil moisture deficits (SMDs) were relatively modest and a notably wet September triggered brisk recoveries in river flows and, subsequently, groundwater levels. These were sustained by a sequence of active low pressure systems through the late autumn and, by December, the focus of hydrological concern had switched decisively to the threat of flooding. The persistence of Atlantic frontal systems over the ensuing two years helped establish very high accumulated rainfall totals nationally and regionally. For England and

Wales the driest 28-month sequence (ending in the summer of 1992) since the 1850s was directly followed by the wettest 32-month sequence this century – ending in February 1995. The wet phase culminated in the 1994/95 winter (December-February) – the wettest for Britain in a series from 1869. Correspondingly, winter runoff accumulations were amongst the highest on record in most catchments, many reported runoff in the 120–170% range, higher for many eastern rivers (see page 18). Groundwater recharge was very healthy also and, from late-1992, groundwater levels in most major aquifers registered their greatest two-year recovery since at least 1976–77 (see hydrographs on pages 150 to 153). The water resources outlook in late February 1995 was exceptionally healthy. Reservoirs were at capacity and groundwater levels close to seasonal maxima over wide areas – the UK appeared very well placed to withstand any spring and summer rainfall deficiency.

TABLE 1 RAINFALL ACCUMULATIONS FOR SELECTED PERIODS WITH ESTIMATES OF RETURN PERIODS

		Apr-Aug 1976	Apr-Aug 1995	Est. Return Period[1]	Apr-Oct 1995	Est. Return Period[1]
England and Wales	mm	155	149		315	
	%LTA	47	46	>200	64	60–90
Scotland	mm	332	314		737	
	%LTA	72	68	35–50	97	2–5
Regions*						
North West	mm	262	215		395	
	%LTA	63	51	120–170	60	80–120
Northumbria	mm	204	162		329	
	%LTA	63	50	>200	70	25–40
Severn-Trent	mm	141	126		257	
	%LTA	48	43	>200	61	50–80
Yorkshire	mm	180	132		258	
	%LTA	58	42	>200	57	120–170
Anglian	mm	130	104		221	
	%LTA	52	42	>200	63	35–50
Thames	mm	110	106		255	
	%LTA	41	40	>200	66	20–35
Southern	mm	91	97		271	
	%LTA	34	36	>200	65	20–35
Wessex	mm	106	138		350	
	%LTA	37	48	80–120	80	5–10
South West	mm	131	187		426	
	%LTA	36	52	70–100	74	10–15
Welsh	mm	199	224		459	
	%LTA	47	53	70–100	68	25–40
Highland	mm	394	379		873	
	%LTA	77	74	10–20	99	2–5
North East	mm	188	273		670	
	%LTA	53	77	5–15	124	10–20
Tay	mm	308	254		651	
	%LTA	79	65	20–35	103	2–5
Forth	mm	313	228		560	
	%LTA	84	61	40–60	94	2–5
Tweed	mm	243	202		458	
	%LTA	69	57	70–100	85	5–10
Solway	mm	341	270		623	
	%LTA	75	59	50–80	83	5–10
Clyde	mm	441	358		814	
	%LTA	86	70	15–25	92	2–5

* National Rivers Authority and River Purification Board regions.
%LTA = percentage of 1961–90 average return periods associated with above average rainfalls are underlined.
Data source: Met. Office.
[1]Return period assessments are based on tables provided by the Met. Office (see reference 8 for details of the procedures followed and justification for the use of a three-parameter log-normal distribution). The tables reflect rainfall variability over the 1911–70 period only and assume a sensibly stable climate. The return periods featured above assume a start in a specified month; return periods for a start in any month may be expected to be around an order of magnitude less – for longer durations the return period estimates converge. The ranking of accumulated rainfall totals for England and Wales and for Scotland can be affected by artifacts in the historical series – on balance these tend to exaggerate the wetness of the recent past.

The 1995 Drought

The frequency of westerly and south-westerly airstreams declined markedly through the early spring of 1995 as a northward extension of the Azores high pressure cell deflected most rain-bearing frontal systems to the north, allowing subtropical air-masses to penetrate across much of the British Isles. Rainfall deficiencies built-up quickly through April and May and a heatwave during much of July and August produced a marked intensification in drought conditions. Much of the late-spring and summer rainfall in 1995 resulted from patchy showers or localised thunderstorms. Some areas, including parts of West Yorkshire, failed to benefit from the spatially highly variable rainfall and experienced particularly intense drought conditions. Substantially below average rainfall was recorded for each of the five months to August 1995 in most regions. Conditions were especially arid in the late summer: August rainfall totals were less than 15% of average throughout much of England and a few localities in the South-East registered zero monthly totals (e.g. in the Brighton and Eastbourne areas). The mean temperature established August 1995 as the second warmest, after July 1983, in the CET series. For England and Wales, the June-August period in 1995 marginally eclipsed 1976 as the driest summer in the 229-year homogenised England and Wales rainfall series[7]. With Scotland registering its second driest summer on record, the June-August rainfall total for Britain also established a new summer minimum in a series from 1869.

Rainfall deficiencies were even more notable in the April-August timeframe; a guide to the regional variation in the rainfall deficiencies, and a comparison with the same period during the 1976 drought, is given in Table 1. The April-August rainfall totals expressed as a percentage of the 1961–90 average are illustrated in Figure 1. The map is based on a 1 km grid of interpolated percentage rainfall values – this degree of resolution helps reveal the substantial regional, and important local variations in drought intensity. Precipitation totals over the five months were below half of the average in most regions with the greatest deficiencies found in a broad zone embracing the greater part of northern England and the English lowlands; the area around Newry and the Mourne Mountains in Northern Ireland was also notably dry. Pockets of extreme rainfall deficiency – less than 20% of the 1961–90 average – could be found in south Derbyshire.

For England and Wales as a whole, the April-August rainfall total is the lowest for *any* five-month sequence in over 200 years; only during the 1921 drought have five-month rainfall totals approaching the 1976 and 1995 minima been registered (see Table 2). Analyses, using standard rainfall frequency tables based on rainfall variability over the 1911–70 period[8], indicate return periods of 150 years or more for the April-August rainfall deficiency for most regions of England. The large spatial variations evident in Figure 1 confirm that the regionally aggregated rainfall figures presented in Table 1 may not be representative across the regions – this is especially true of the Yorkshire and Severn-Trent regions. In addition, caution should be exercised in interpreting the return periods quoted in Table 1 (see footnotes); the assumption of a stable climate, in particular, may prove unrealistic (see below).

TABLE 2 5-MONTH MINIMUM RAINFALL TOTALS FOR ENGLAND AND WALES, 1800–1995

Rank	Rainfall (mm)	% of 1800–1995 average	End month/yr
1	149	43.1	08 1995
2	155	44.8	08 1976
3	159	50.7	06 1921
4	184	58.7	06 1938
5	185	56.7	07 1826
6	185	59.0	06 1929
7	186	59.3	06 1887
8	187	52.4	04 1854
9	188	57.6	07 1870
10	191	48.8	03 1858
11	191	52.1	09 1959
12	193	59.1	07 1990

The exceptionally low rainfall, coupled with hot, sunny conditions which resulted in evaporation demands exceeding the average, typically by 20%, meant that some stress on water resources and river systems was unavoidable during 1995. River flows and groundwater levels generally remained well within the normal range through the spring but, by May, steep and protracted recessions had produced well below average flows in most regions. A clear distinction could, however, be drawn between rivers draining impervious western and northern catchments and rivers in the English lowlands supported principally from groundwater. In the latter, baseflows kept summer runoff rates well above drought extremes; most 1995 minima were not registered until late in the year (see page 18). In more responsive catchments, however, exceptionally low runoff rates were reported during the summer. For instance, in Scotland during the latter half of August unprecedented minima were registered on the Dulnain (Highland Region) and the West Peffer Burn (Lothian Region) reported a zero flow for the first time in a record from 1966. New minimum monthly runoff totals were established at around 20% of primary gauging stations in the UK with 15 or more years of record. Their distribution – from northern Scotland to Cornwall testifies to the spatial extent of severe drought conditions. Flows in some Pennine rivers were especially depressed: the Coalburn (Cumbria) registered its first zero monthly runoff in a 30-year record and the August flow on the River Ure (Yorkshire) was only around 60% of the previous minima (established during the 1976 drought).

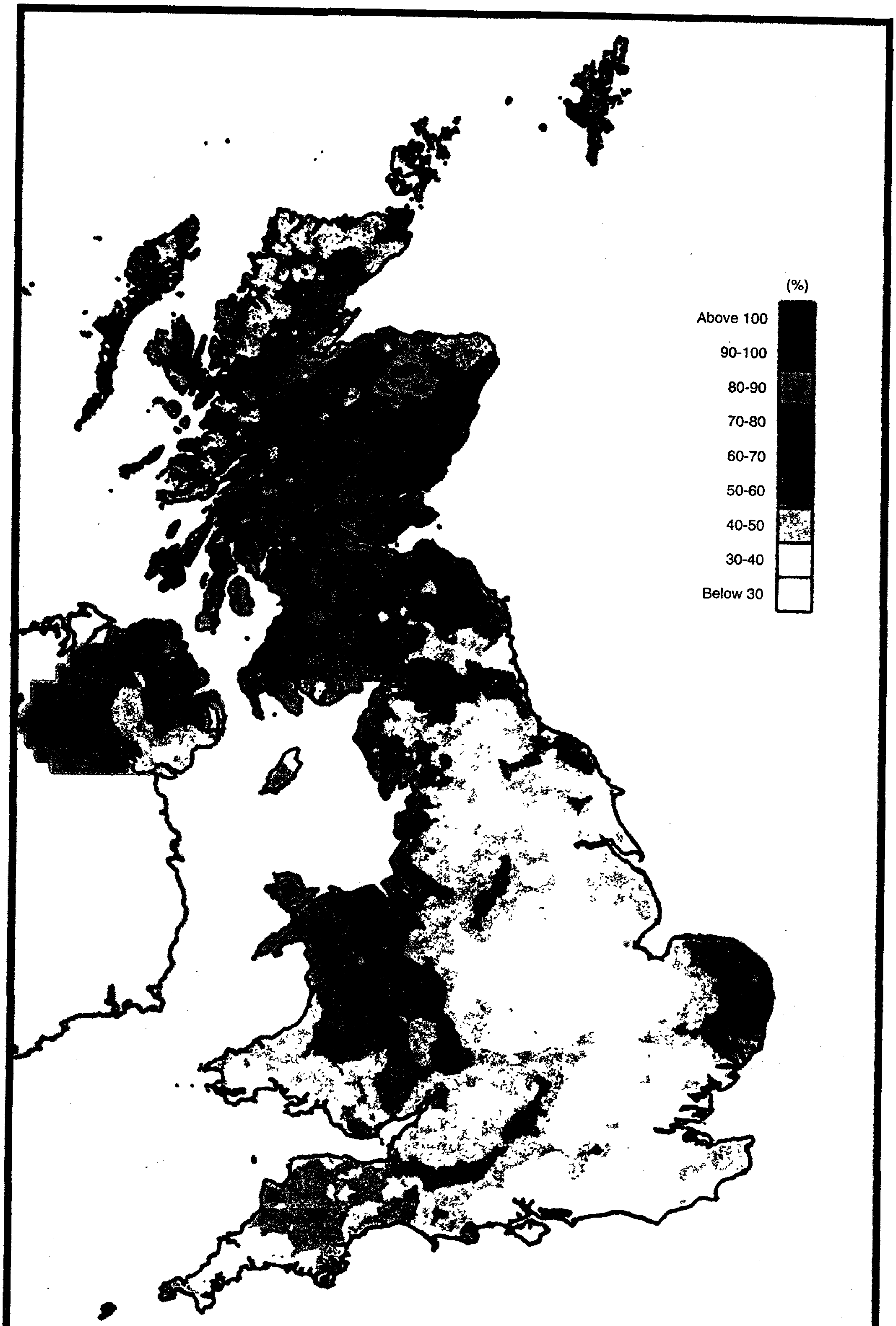

Figure 1 April–August rainfall in 1995 – as a percentage of the 1961–90 average

Water Resources Impacts

Although relatively healthy groundwater levels provided a valuable buffer against the effects of the dry spring and summer in 1995, unprecedented water demands began to reveal weaknesses in the water distribution networks as the drought developed. Peak summer demands in recent years have been exceptional[9]. In eastern England particularly, this results in part from the growth in water use for irrigation[10] but a more significant factor, nationally, during 1995 was the surge in demand – normally concentrated in the evening – caused by garden watering during extended hot, dry spells. The patchy response to publicity campaigns to moderate water usage resulted in a number being quickly followed by the introduction of hosepipe bans; these extended over an ever increasing area. At this stage of the drought's development, local – and mostly temporary – water distribution problems created the illusion of national water resources stress and posed considerable public relations difficulties for the water industry, at a time when overall resources were relatively healthy.

Around mid-July, the drought entered a transitional phase as the mismatch between resource depletion and replenishment produced rapidly dwindling reservoir stocks. This was most evident in those areas supplied from small reservoirs or those not yet fully integrated into regional networks (e.g. in Cornwall and West Yorkshire). By late August the drought had intensified markedly and in some, mostly western and northern, areas stocks in a number of major reservoirs (for example in the Pennines and the Lake District) had declined to below 20% of capacity; a real threat to resources thus became established. Hosepipe bans were extended over an ever increasing area through the summer and entering the autumn almost 20 million people were affected.

Rainfall deficiencies over the April-August period were more exceptional in parts of the English lowlands than in the north, but the water resources outlook was of less immediate concern because groundwater levels in the Chalk, England's most important aquifer, remained mostly within the normal range – a consequence of the abundant rainfall throughout the winter of 1994/95. The groundwater level variation at The Holt and Washpit Farm boreholes (see page 150) provides a representative confirmation of the generally healthy state of groundwater resources through the spring and summer of 1995, the hydrographs also illustrate the remarkable range experienced over an eight-year period characterised by wide and sustained departures from the normal seasonal variation.

A Modest Droughtbreak followed by Re-intensification

Early September witnessed a further marked change in weather patterns with a sequence of active frontal systems sweeping across most regions. Several southern areas recorded more rainfall over the first 10 days of September than in the preceding 10 weeks and localised flooding was widely reported. A repetition of the dramatic end to the droughts of 1976 and 1984 seemed possible as the second driest August on record, for the UK as a whole, was followed in parts of southern England by the second wettest September. This encouraging transformation – and the decline in evaporation demands as the growing season came to an end – greatly eased the water supply stress. However, a number of strategically important reservoir systems, including those in the Pennines and the Lake District, failed to benefit from the early autumn rainfall and, with soils still dry in most catchments, the seasonal recovery in runoff and recharge rates was weak and patchy.

Throughout most of England and Wales, October was relatively dry and remarkably mild – concluding the warmest 12-month sequence in the entire CET series. The synoptic pattern began to change again in November as persistently anticyclonic conditions to the north of the British Isles allowed airflows from the north-easterly quadrant to become dominant. These brought cold and dry conditions which were to continue through much of the 1995/96 winter. The paucity of rain-bearing frontal systems through the late autumn of 1995 produced a re-intensification in the drought. Particularly severe drought conditions again affected the southern Pennines where, for some reservoired catchments, the accumulated rainfall deficiencies since March – in a timeframe critical for water resource management – were the highest on record. Stocks in a few West Yorkshire reservoirs fell to below 15% of capacity and tankering was required to counteract the rapid drawdown and to maintain supplies in parts of the region. For England and Wales as a whole, overall stocks declined to below the minima registered in the drought years of 1989 and 1990. By early December the drought had significantly increased its range – extending down into East Anglia and north Wales, but the focus remained in northern England, the North-West especially. Some Pennine raingauges had recorded 10 successive months with below average rainfall by year-end and accumulated totals were the lowest in 100 years or more[11]. A cold December with substantial snowfall moderated the drought but thereafter the winter remained cool and dry and rainfall deficiencies again increased in 1996.

River flow recessions continued through much of October and November in most areas resulting in exceptionally low accumulated runoff totals for timespans exceeding about two months. The flow frequency diagram for the River Wharfe (Figure 2) illustrates the increase in drought intensity over the longer timeframes. The 1995 60-day minima is notable but appreciably above those established in 1976 and 1959. When 120-day minima are consi-

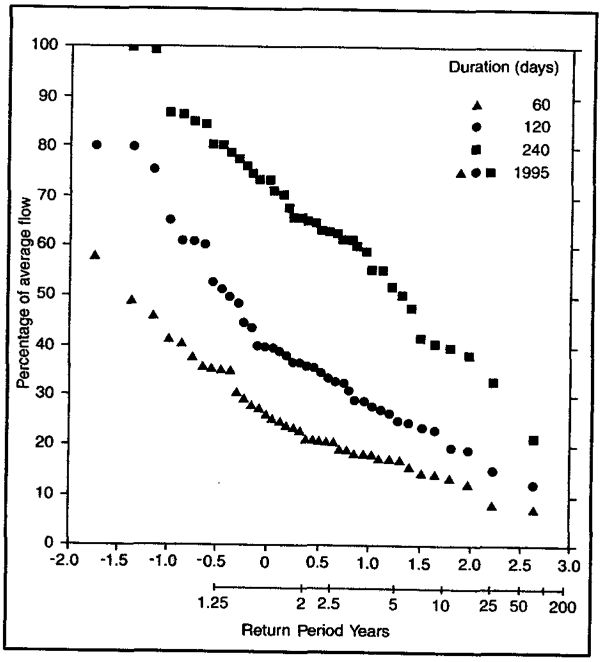

Figure 2 Flow frequency diagram for the River Wharfe

dered, only 1959 produced lower runoff and for 240-day accumulations the 1995 minima is unprecedented; Figure 2 indicates that such flows may be expected on average only once in 80–120 years (assuming a sensibly stable climate). Away from northern England, 1995 runoff deficiencies were less extreme but April-November runoff totals were the lowest on record throughout much of northern Britain and the Midlands.

By December, water-table recessions had commonly extended over nine months and early winter groundwater levels testified to an exceptional decline since the late winter of 1994/95. In some areas – for example the South Downs where groundwater levels at the Chilgrove House borehole had fallen more than 40 metres since February – drought minima were being approached by year-end and concern focused on the general water supply prospects for 1996*.

The Recent Past

Water management in the United Kingdom, as elsewhere, is underpinned by the lack of trend in long term river flow and groundwater level series, some of which extend back 150 years. In a climate as variable as that of the UK any short term deviation from the average needs to be treated with considerable caution particularly as the clustering of wet or dry years is known to be a feature of the climate of western Europe[12]. Nonetheless, the hydrological characteristics of the last 25 years – and their broad consistency with a number of favoured climate change scenarios[13,14] -imply that any assumptions of a continuing stationarity in runoff and aquifer recharge series need to be kept under continuing review.

Average temperatures over the seven years ending in 1995 are the highest on record and for the last 20 years, taken together, mean temperatures have been around 0.5°C greater than the preceding average. Correspondingly, evaporation losses have been notably high; lower relative humidities and increased average wind speeds may also have enhanced evaporation rates in recent years. Potential evaporation losses for the 1990s have been substantially greater than those which typified the 1960s[1]. This is of particular significance in eastern and southern England where, on average, annual potential evaporation totals exceed rainfall, and concentrations of population, commercial activity and intensive agriculture generate the greatest demand. However, it is also important in western and northern catchments where increased actual evaporation losses could significantly reduce reservoir yields.

During most recent years one consequence of the elevated evaporative demands has been the persistence of substantial soil moisture deficits well into the autumn. Commonly, end-of-October SMDs have exceeded 70 mm in much of the English lowlands. In a normal year such deficits would require around two months average rainfall to be satisfied in the east. If the ensuing winter is dry, runoff rates recover only sluggishly and the window of opportunity for aquifer recharge can be narrowed down to a matter of weeks. Such circumstances prevailed in eastern England during successive winters in the extended drought of 1988–92 (and again in 1995/96). Over the full compass of the 1988–92 drought the combination of very dry autumn soils, limited winter rainfall and enhanced evaporation losses was to translate a 20% rainfall deficiency into a 50% reduction in recharge to the Chalk and Upper Greensand aquifers[3].

A contributory factor to the dryness of summer soils has been the recent tendency for a more distinct partitioning of rainfall between the winter and summer half-years. Normally rainfall in Britain is fairly evenly distributed through the year and the ratio of October-March rainfall totals to those of the following summer half-year displays no overall trend over the first 100 years of the series. Since the early 1970s however, the ratio has increased significantly[15]. In part this reflects the cluster of record winter rainfall totals for Scotland; seven of the wettest eight October-March periods have occurred

* Although February 1996 was wet, rainfall deficiencies continued to build through the spring and early summer. By the end of September, the rainfall deficiency for England and Wales since March 1995 ranked third greatest (after the 18-month minima established in the 1883/5 and 1975/6 droughts) in the last 200 years at least.

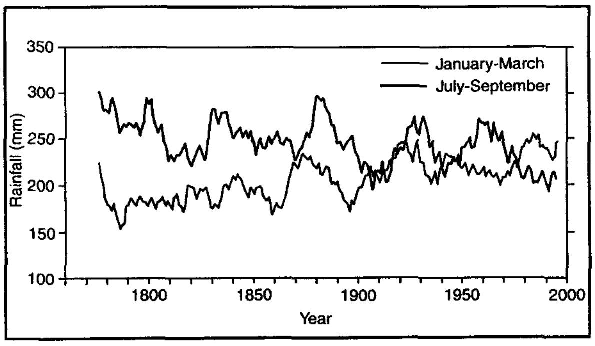

Figure 3 Jan-Mar and July-Sept rainfall for England and Wales (10-year running means)

since 1986/87 (but see footnote on page 9) and the precipitation totals for the Highlands have been outstanding. A tendency towards wetter winters and drier summers is also clearly evident in the England and Wales series. Figure 3 compares January-March rainfall totals for England and Wales with those for July-September. Both traces show compelling but opposing trends. However, in the eighteenth and early nineteenth century inadequacies in the rain-gauge network (e.g. the very sparse initial coverage in the western uplands) limit the reliability of the seasonal totals – the winter especially. Latterly, it has also been confirmed[16] that artifacts in the series result from the manner in which the national dataset has been computed. However, the divergence of the running mean plots from the early 1960s is based on consistently derived monthly totals and has no modern parallel.

The very unusual temporal distribution of rainfall in the recent past have been accompanied by an equally marked change in spatial patterns. A clear exaggeration in the north-west/south-east rainfall gradient across the UK may be demonstrated[15,17]. Figure 4 illustrates the relationship between annual precipitation totals for Fort William and Kew. The preferred tracks of Atlantic low pressure systems over the post-1970 period (until late-1995) contributed to a sharp increase in the relative wetness of Fort William; this tendency is confirmed by regional rainfall comparisons. Generally, the effect of evapo-

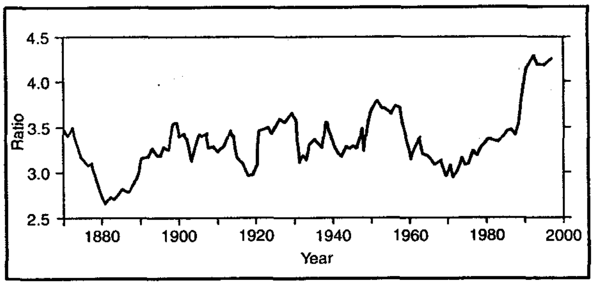

Figure 4 Ratio of the annual rainfall at Fort William to annual rainfall at Kew (10-year running mean)

ration losses has been to further accentuate regional contrasts in rates of runoff and aquifer recharge.

The unusual nature of the climate of England and Wales over the 1976–95 period is encapsulated in Figure 5 which shows rainfall and temperature anomalies for the post-1844 period. The April-August and November-March periods were chosen to reflect the importance of the two periods in relation to the replenishment and depletion of water resources; coincidentally they help to emphasise the singular nature of the hydrological transformation over the 1994/96 period. Recent autumn/winter periods exhibit wide departures from the average and a modest tendency to cluster in the warm/wet quadrant. The April-August data exhibits much more marked clustering; the 1976 and 1995 spring/summer periods are outstanding but most group in the warm/dry quadrant – over the last 20 years summer rainfall is 10% below, and temperatures 0.6°C above the preceding average. Examination of the full England and Wales rainfall series reveals a few precedents to the recent volatility in rainfall patterns, for example in the 1850s. However, once account is taken of temperatures and evaporative demands, there are no close analogues in the hydrological record to the recent past.

The interplay of rainfall amounts, evaporative losses, catchment geology and the evolving pattern of water utilisation in individual catchments has resulted in complex variations in flow regimes over the last 20 years, the recent past especially. Nonetheless, flow regimes for many rivers echo – in many cases accentuate – the increased seasonality exhibited by rainfall. This regime variation is superimposed on changes in overall runoff totals which display a clear regional pattern. Figure 6 shows the change in monthly runoff since 1987 relative to the preceding record for four catchments with relatively minor disturbance to the natural flow regimes. For the River Clyde overall runoff over the 1988–95 period is substantially above average with significantly increased flows through much of the winter. This contrasts with catchments in eastern and southern England. Overall runoff has been well below average on the Rivers Lymington and Waveney and July-October runoff totals have been notably low – contributing to enhanced seasonality. For the spring-fed Mimram (see page 17) which drains a Chalk catchment in Hertfordshire, above average winter rainfall over the 1988–95 period has resulted in increased baseflows to support summer discharge and thus only a very muted change in seasonality is evident on Figure 6. Whilst these results show broad similarities with postulated regime changes associated with global warming[14], regime variation over short runs of years are common and a more comprehensive and ongoing analysis will be required to determine whether the last decade represents the beginning of a real departure from the seasonality captured in the historical record.

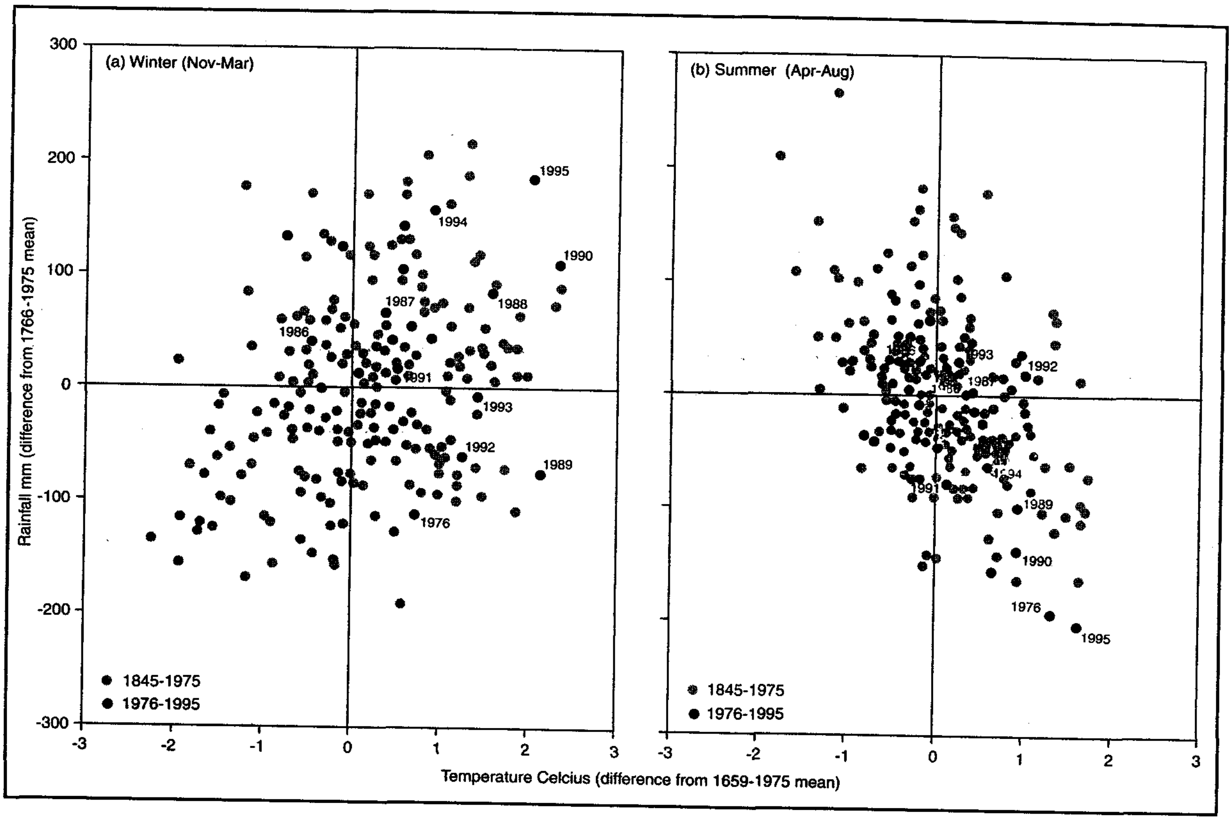

Figure 5 England and Wales rainfall and Central England Temperature anomalies 1845–1995

Conclusion

Hydrologically, the wide departures from average seasonal conditions which have been a feature of the 1990s achieved an extreme expression over the 1994/95 period when temperatures and rainfall patterns were more typical of western France. Whilst rainfall, temperature and soil moisture interactions can have subtle water resource implications, enhanced winter rainfall will generally bring obvious benefits. Importantly however, 1995 and 1990 have both demonstrated how rapidly runoff rates can decline and water supply prospects deteriorate. 1995 saw almost 20 million people affected by hose/sprinkler bans and, in a few areas, the threatened introduction of rota cuts or standpipes (which, in the event, were not required). This produced considerable consumer resentment and political comment. The use of measures to restrict demand during 1995 was, however, unsurprising given the inordinate nature of the spring and summer rainfall deficiency. In the perspective provided by lengthy historical rainfall and temperature records (up to the mid-1970s), the level of risk adopted for resource management purposes in the UK appears to be of the right order – and was largely vindicated during the droughts of 1976 and 1984. But consumer willingness to reduce their water demand may well be changing; importantly so also may the climate. Singular as the conditions experienced in the 1995 summer were, notably hot and dry periods also occurred in 1994 (briefly), 1990, 1989, 1984 and 1983. This suggests that the historical rarity of drought events may no longer be a reliable guide to their contemporary frequency. It is too early to incorporate projections of the impact of global warming into detailed national or regional water resource management strategies; but to continue to give equal weight to modern and historical hydrometric data when indexing the rarity of contemporary droughts may no longer retain scientific and public credibility. Recent data suggest that return periods based on standard historical periods may no longer be fully representative and that water management contingency planning should focus on a substantially higher incidence of periods of water resources stress.

Acknowledgments

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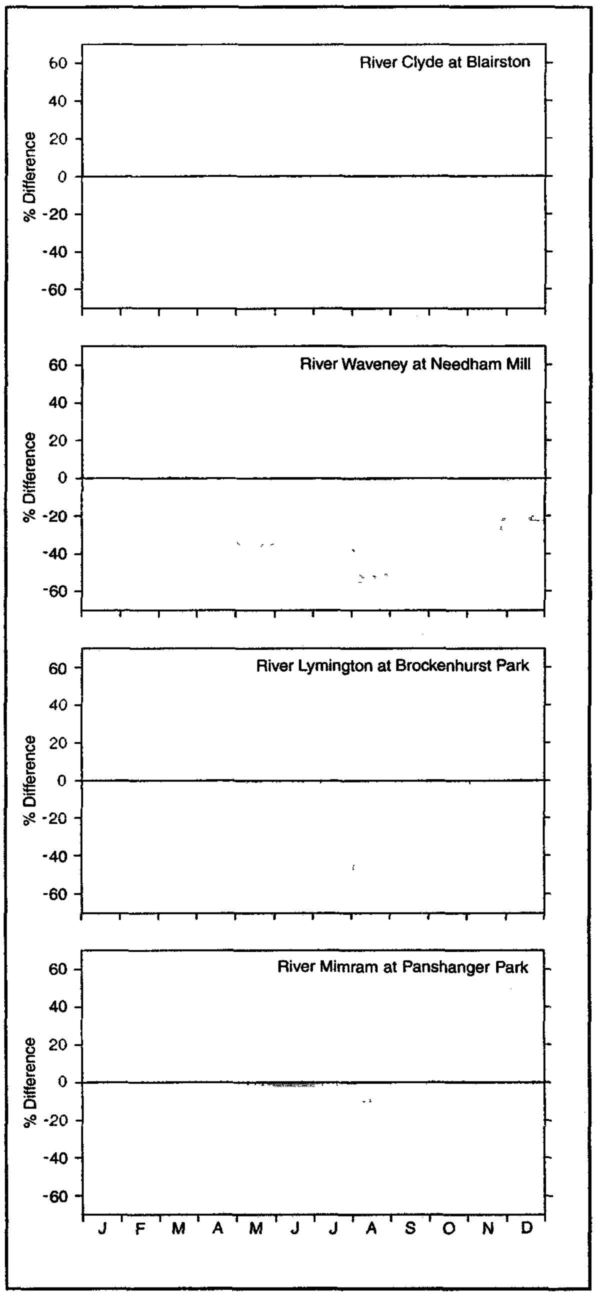

Figure 6 *Change in monthly runoff since 1987 relative to the preceding record expressed as a percentage difference*

regional divisions of the Environment Agencies. Reservoir contents data are provided by water companies and regional authorities and most of the rainfall data (and updates of the CET series) is supplied by the Met. Office. For historical comparisons the homogenised England and Wales rainfall series derived by the Climatic Research Unit, University of East Anglia[7] was used. The level of cooperation sustained by the data producers is gratefully acknowledged.

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References

1. Marsh, T.J. (1996) The 1995 drought – a signal of climatic instability. Proc. Instn. Civ. Engrs. Wat., Marit. & Energy, 118, Sept., 189–195
2. Anon. (1993) 1992 Yearbook, Hydrological data UK series Institute of Hydrology, 184pp.
3. Marsh, T.J., Monkhouse, R.A., Arnell, N.W., Lees, M.L. and Reynard, N.S. (1994) The 1988–92 Drought. Hydrological data UK series. Institute of Hydrology, 82 pp.
4. Hamlin, M.J. and Wright, C.E. (1978) The effects of drought on the river systems. In: Scientific aspects of the 1975–6 drought in England and Wales. Proc. Roy. Soc. London, Series A, Vol. 363, 69–96.
5. Marsh, T.J. and Lees, M.L. (1986) The 1984 Drought. Hydrological data UK series. Institute of Hydrology, 72pp.
6. Manley, G. (1974) Central England Temperatures: monthly means 1659 to 1973. Quart. Jour. Royal. Met. Soc., 100, 389–405.
7. Wigley, T.M., Lough, T.M. and Jones, P.D. (1984) Spatial patterns of precipitation in England and Wales and a revised, homogeneous England and Wales precipitation series. Jour. Clim. Vol. 4, 1–25.
8. Tabony, R.G. (1977) The variability of long duration rainfall over Great Britain. Met. Office Scientific Paper No. 37.
9. Anon. (1995) Demand for water hits new peaks. Demand Management Bulletin, No.12, August 1995. National Rivers Authority Demand Management Centre.
10. National Rivers Authority. (1994) Water – Nature's Precious Resource. HMSO, 26–27.
11. Anon. Monthly rainfall report. Environmental Agency NW Region.
12. Arnell, N.W. and Reynard, N.S. (1993) Impacts of climate change on river flow regimes in the United Kingdom. Report to the Dept. of the Environment.
13. Rowntree, P.R., Murphy, J.M. and Mitchell, J.F.B. (1993) Climatic change and future rainfall predictions. Journ. I.W.E.M., 7, 464–470.
14. Arnell, N.W and Reynard, N.S. (1996) The effects of climate change due to global warming on river flows in Great Britain. Jour. of Hydrology (in press).
15. Green, S., Sanderson, F.J. and Marsh, T.J. (1996) Evidence for recent instability in rainfall and runoff patterns in the Celtic regions of western Europe. Proc. Inter-Celtic Colloquium, Rennes, July 1996 (in press).
16. Woodley, M.R. (1996) A review of two national rainfall series. Int. Jour. Clim. Vol. 16, 677–687.
17. Mayes, J.C. (1995) Changes in the distribution of annual rainfall in the British Isles. Journ. CIWEM, 9, 531–539.