National Hydrological Monitoring Programme

THE 2004-06 DROUGHT

Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

British Geological Survey
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This report reviews the 2004-06 drought within a hydrological and water resources framework. It was prepared as part of the National Hydrological Monitoring Programme (NHMP) – a collaborative enterprise between the Centre for Hydrology and Ecology and the British Geological Survey (both component bodies of the Natural Environment Research Council). The NHMP relies on the active cooperation of many organizations - the Environment Agency, Scottish Environment Protection Agency, Rivers Agency (Northern Ireland) and the Met Office in particular. The provision of the basic data which provides the foundation both of this report and the wider activities of the NHMP is gratefully acknowledged.

A primary source of information for this review is the series of monthly UK Hydrological Summaries (for further details please visit: http://www.ceh.ac.uk/data/nrfa/water_watch.html).

Authors

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Cover photo: River Pang in Berkshire, August 2005

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The 2004-06 Drought

Introduction

This report documents the 2004-06 drought in a hydrological framework with particular reference to its impact on water resources and the aquatic environment. The drought is also examined within the context of hydrological variability over the last 30 years and an overview is provided of its relative severity and impact when compared with other major drought episodes in England and Wales over the last 200 years. For a more detailed documentation of the development and decay of the drought, please visit the National River Flow Archive's 'Water Watch' website at:

http://www.ceh.ac.uk/data/nrfa/water_watch.html

Some of the data used to characterise the 2004-06 drought are of a provisional nature and may be subject to future revision.

Background

Droughts are multifaceted both in their character and range of impacts. Indexing drought severity is far from straightforward, reflecting the difficulties in quantifying a phenomenon which varies in its extent, duration and intensity both regionally and locally. Distinctions can be drawn between meteorological droughts – defined essentially on the basis of rainfall deficiency; hydrological droughts – where accumulated shortfalls in runoff and aquifer recharge are of primary importance, and agricultural droughts – where the availability of soil water through the growing season is the critical factor. The unusual temporal distribution of rainfall throughout most of the 2004-06 period implies that rainfall deficiencies alone provide a very incomplete index of drought intensity. Correspondingly, runoff patterns and, especially, groundwater levels provide more convincing measures of the drought's magnitude. In this report emphasis is placed on water resources impacts with some discussion of the environmental consequences, the loss of aquatic habitat in particular.

Overture to the 2004-6 drought

The last decade has been hydrologically volatile across much of the UK. Protracted drought conditions in the mid-1990s, with exceptionally depressed groundwater levels, were followed by the wettest 5-year sequence in the England and Wales rainfall series which begins in 1767[1]. Whilst Scotland registered several periods of major rainfall deficiency, damaging flooding was a recurring feature in southern Britain. Outstanding winter rainfall in 2000/01 resulted in groundwater levels reaching unprecedented maxima over wide areas. Abundant water resources characterized most of England and Wales over this period, and continued into the winter of 2002/03.

The spring, summer and autumn of 2003 were exceptionally warm and dry. England and Wales registered its second lowest February-October rainfall in 83 years; as remarkably, Scotland reported its driest 9-month sequence (for any start month) since the 1955 drought[2]. By July severe drought conditions extended across much of western and central Europe. In contrast to mainland Europe, where the drought was of a lesser duration, more intense, and triggered a review of drought management in many European countries, the UK was subject to relatively minor water resources and environmental stress. The 2003 drought underlined the resilience of the UK's water supply capabilities to even major within-year rainfall deficiencies when the preceding winter has been sufficiently wet to leave surface and groundwater resources in a healthy state[3].

However, the very dry autumn soil conditions in 2003 delayed the onset of the seasonal recovery in runoff and, particularly, aquifer recharge rates throughout much of the English Lowlands. The continuing groundwater level recessions in parts of the Chalk (the primary source of water supply in much of eastern and southern England) left early winter levels at their lowest since 1997 in some areas. Correspondingly, the spring groundwater level recessions in 2004 began at below average levels and the failure of the seasonal recovery to gain any momentum through the autumn signalled the onset of sustained drought conditions, in the South East especially.

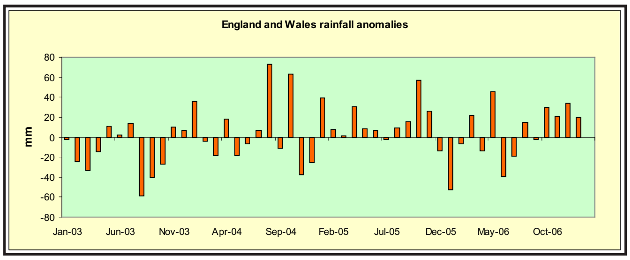
Overview of the drought

Taken together, 2005 and 2006 constitute the warmest two-year sequence in the 337-year Central England Temperature series[3]. The summer periods included several notably arid episodes (e.g. June 2006) but the water resources and environmental impacts of the 2004-06 drought largely reflected the lack of rainfall over two successive winter/spring periods. Drought conditions developed through the late autumn of 2004 across much of the English Lowlands and lasted, in most areas, until the early winter of 2006/07. Whilst the elevated temperatures in 2004-06 are consistent with a continuing warming trend, successive notably dry winters are unusual in the context of the last 30 years. Prior to the 1st World War however, clusters of dry winters were substantially more common with November-April rainfall totals in the English Lowlands often less than for the summer half-year[4]. The 2004-06 drought has served to emphasise the continuing vulnerability of England and Wales particularly, to low winter rainfall. It also underlines the need to understand more fully the mechanisms which contribute to multi-decadal climatic variability in the UK.

The 2004-06 drought had a strong regional focus and was generally most severe in the driest parts of the UK where groundwater is the major source of water supply and a combination of high population density, intensive agriculture and commercial activity generates the highest water demand. Careful management was required to reconcile the needs of a wide range of water users with the requirements of the aquatic environment.

Rainfall

Notwithstanding a notably wet November in 2003, significant rainfall deficiencies were carried over into the following year. From the late autumn of 2004, persistent anticyclonic conditions across southern Britain resulted in most rain-bearing low pressure systems following tracks remote from the English Lowlands. This resulted in a notable exaggeration in the normal north-west/south-east rainfall gradient across the UK. Parts of north-west Scotland were very wet whilst large rainfall deficiencies became established across much of eastern, central and southern England. The regional dimension to the drought was reinforced in the first four months of 2005 when rainfall totals for England and Wales were considerably above average whilst much of the South East registered its 2nd lowest January-April rainfall since 1976 (see Figure 1).



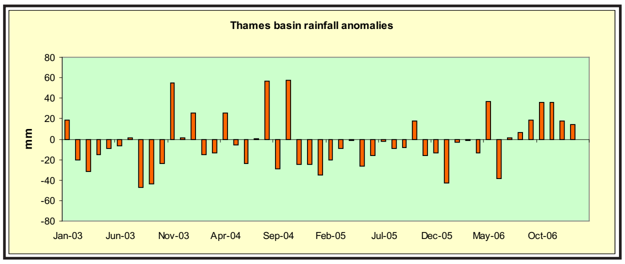


Figure 1 2003-06 monthly rainfall anomalies

Considering, the drought-affected region as a whole, rainfall deficiencies were most severe over the 21 months ending in July 2006. In this timeframe England and Wales reported its 3rd lowest rainfall since 1932-34 with the most exceptional regional deficiencies in the Thames and Southern regions (see Table 1). Figure 2 illustrates the 21-month rainfall deficiencies across southern Britain relative to the 1961-90 average. Maximum deficiencies exceeded 25% – mostly in the South East but notable drought conditions also extended into parts of the Midlands and the South West, Cornwall especially. Figure 2 also testifies to the very substantial local variations in drought intensity, due in part to the convective nature of much of the summer and early autumn rainfall.

Table 1 Minimum 21-month rainfall totals (ending in July) (data from 1914)

	England and Wales			Thames Region			Southern Region		
Rank	Total (mm)	% of lta	End yr	Total (mm)	% of lta	End yr	Total (mm)	% of lta	End yr
1	1187	76.6	1934	868	71.5	1934	985	72.4	1934
2	1220	78.9	1976	922	76.0	1922	990	72.8	1922
3	1318	85.0	1922	944	77.8	1976	1050	77.2	2006[3]
4	1332	85.9	1997	949	78.2	2006[2]	1063	78.1	1944
5	1355	87.4	2006[1]	956	78.8	1944	1094	80.4	1949
6	1355	87.4	1944	995	82.0	1997	1095	80.5	1973

Note: 1 Ranks 8th for 21-month accumulations for any start month
2 Ranks 7th for 21-month accumulations for any start month
3 Ranks 7th for 21-month accumulations for any start month

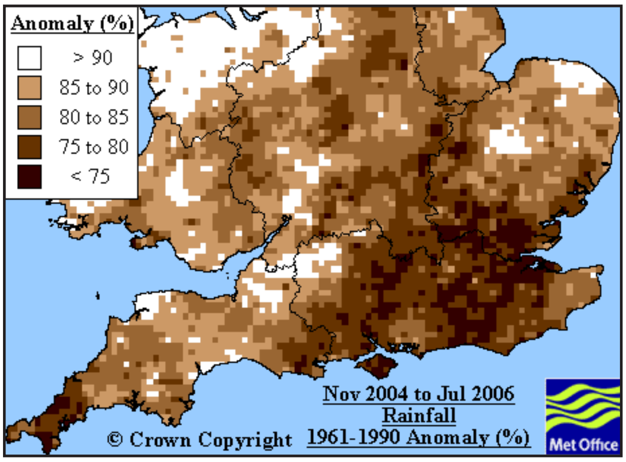


Figure 2 November 2004-July 2006 rainfall anomalies

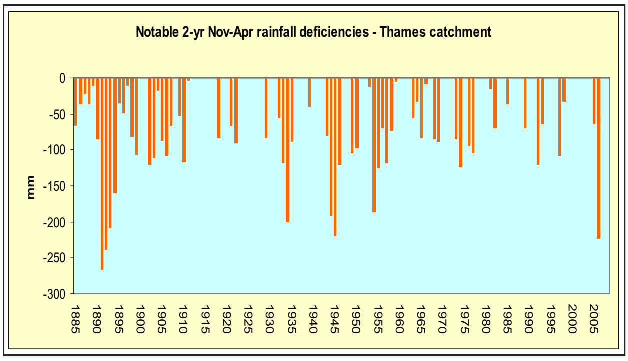


Figure 3 Two-year winter-spring rainfall deficiencies for the Thames basin

Of primary significance from a water resources perspective was the disproportionate concentration of the overall rainfall deficiency in the winter and spring – when modest evaporation losses allow the bulk of reservoir replenishment and aquifer recharge to take place. The paucity of winter and early spring rainfall across much of southern Britain during the 2004-06 period is evident from Figures 3 and 4. The former uses the 124-year catchment rainfall series for the Thames to provide a lengthy historical perspective, and confirms that the combined November-April[1] catchment rainfall deficiencies for 2004/05 and 2005/06 is the largest for over 100 years (marginally eclipsing 1944-46). The relatively low frequency of clusters of dry winter/spring periods in the recent past is a significant feature of Figure 3.

In most drought-affected regions, rainfall over the two summer half-years (May-October) was within the normal range, and close to the average across much of the South East where a relatively dry 2005 was balanced by above average rainfall in 2006. Temporal variations in summer half-year rainfall did, however, impact on the drought's severity in 2006. After a damp late spring, the drought re-intensified through June and July which, taken together, were the 2nd driest in the last 23 years for England and Wales. Correspondingly, soil moisture deficits increased steeply and the region subject to drought stress extended. Rainfall deficiencies began to moderate through an unsettled late summer and the drought's intensity weakened substantially through the autumn of 2006 (see page 22).

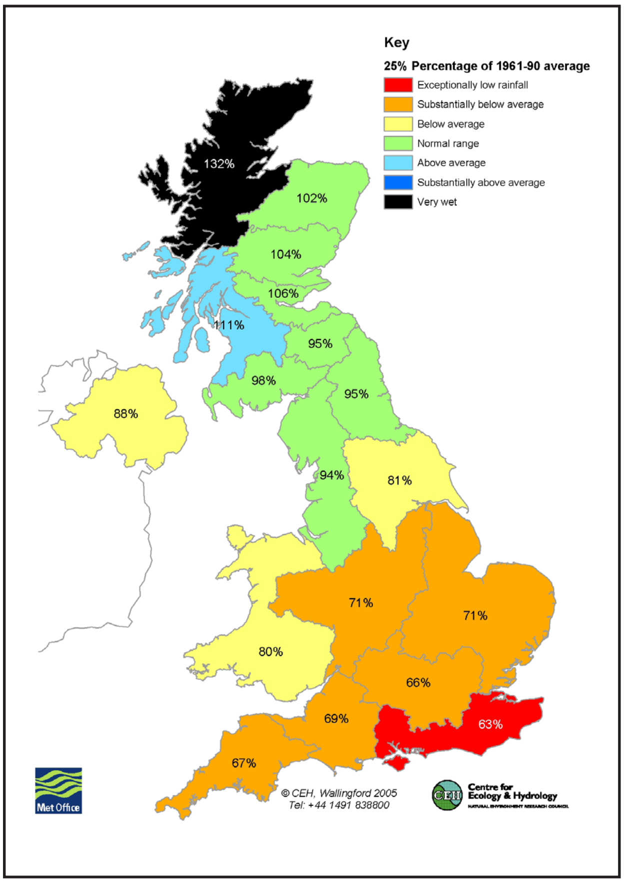


Figure 4a November-April rainfall as a % of the 1961-90 av. for 2004/05

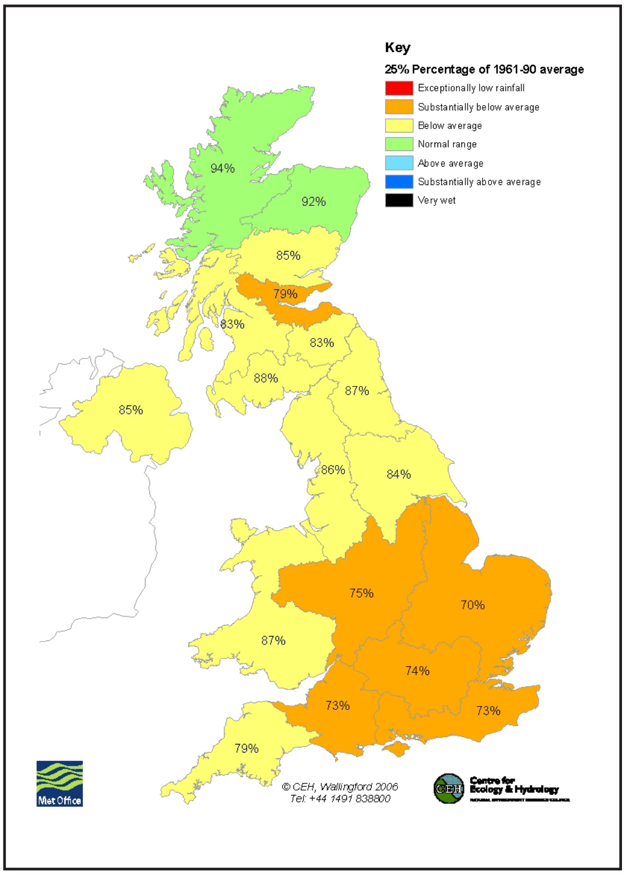


Figure 4b November-April rainfall as a % of the 1961-90 av. for 2005/06

River Flows

Throughout 2004-06, river flow patterns in the drought-affected regions were notable for an exceptional lack of spates and outstanding long term runoff deficiencies. Generally however, annual minimum flows were less notable and, in most areas, remained significantly above recent drought minima.

In runoff terms the drought's duration varied appreciably across southern Britain but, generally, flows remained seasonally depressed from the late autumn of 2004 to the autumn of 2006 – later in many slow-responding spring-fed rivers in the English Lowlands. Of particular hydrological interest over this period was the virtual absence of high flow events. For the Thames at Kingston, no daily flow (naturalised) exceeded Q_{10} during the 29 months to October 2006, the longest such sequence for over 100 years. In relation to water resources stress, the associated long term runoff deficiencies were of more direct relevance. Figure 5 shows November 2004–August 2006 runoff totals expressed as a percentage of the long term average for a network of index catchments across the UK. In this timeframe, runoff was below average across almost all of the country but the largest deficiencies – exceeding 30% – were mostly confined to central and southern England. New minimum 22-month runoff totals (for periods beginning in November) were established from Cornwall to Kent (see Table 2; the featured rivers are shown on Figure 5). A significant minority of these minima represented the lowest runoff for *any* 22-month period and some, including those for the Medway and the Sussex Ouse, eclipsed previous minima by a considerable margin. Elsewhere, the 22-month minima were, typically, a little greater than those registered during the protracted droughts of the early and mid-1990s. In rivers with a high baseflow component flows continued to decline well into the autumn. For the Thames, the November 2004-September 2006 runoff was the lowest since 1947-49.

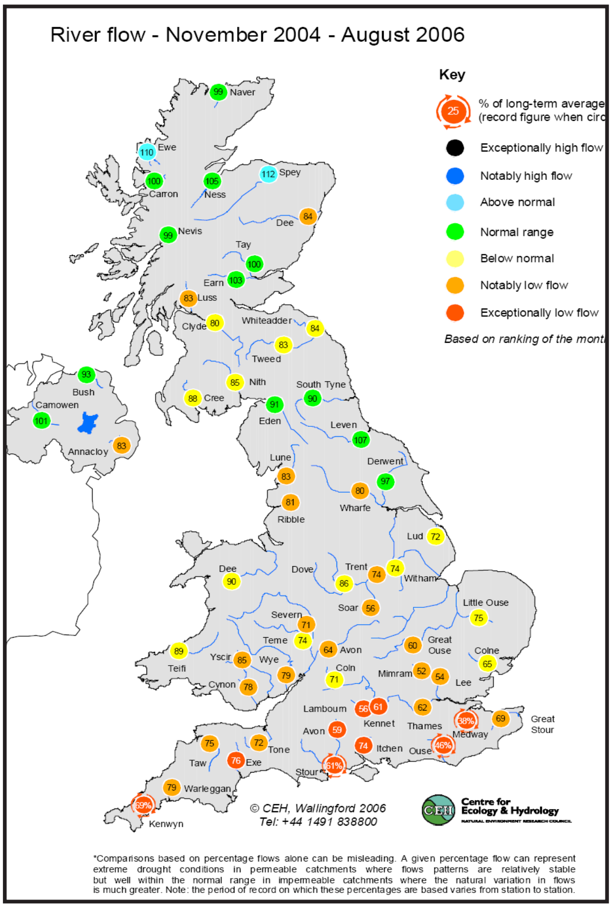


Figure 5 November 2004 – August 2006 runoff accumulations as a % of the long term average

Table 2 22-month runoff totals ending in August

River Soar at Littlethorpe (record: 1971-2006)

Rank	*Runoff (mm))*	*% of lta*	*End year*	*Rank (any start mth)*
1	238	55.1	1997	
2	**250**	**58.1**	**2006**	**4th**
3	291	67.5	1992	
4	**299**	**69.3**	**2005**	**4th**
5	308	71.3	1976	
6	309	71.7	1998	

River Mimram at Panshangar Park (record: 1952-2006)

Rank	*Runoff (mm))*	*% of lta*	*End year*	*Rank (any start mth)*
1	112	49.0	1992	
2	113	49.5	1974	
3	115	50.4	1998	
4	**122**	**53.3**	**2006**	**4th**
5	140	61.4	1997	
6	162	80.0	1973	

(Note: the 22-month period ending in 12/06 is the lowest for any start month

River Thames at Kingston (naturalised flows: 1951-2006)

Rank	*Runoff (mm))*	*% of lta*	*End year*	*Rank (any start mth)*
1	262	55.0	1992	
2	**291**	**61.2**	**2006**	**3rd**
3	301	63.2	1997	
4	332	69.8	1998	
5	347	72.9	1974	
6	352	74.0	1965	

River Medway at Teston (record: 1956-2006)

Rank	*Runoff (mm))*	*% of lta*	*End year*	*Rank (any start mth)*
1	**207**	**40.4**	**2006**	**1st**
2	271	53.0	1992	
3	**301**	**58.8**	**2005**	**4th**
4	321	62.7	1997	
5	352	68.7	1993	
6	384	75.0	1990	

River Kenwyn at Truro (record 1968-2006)

Rank	*Runoff (mm))*	*% of lta*	*End year*	*Rank (any start mth)*
1	**837**	**71.8**	**2006**	**4th**
2	**857**	**73.5**	**2005**	**4th**
3	923	79.2	1992	
4	994	85.3	1997	
5	1000	85.8	1976	
6	1003	86.1	1985	

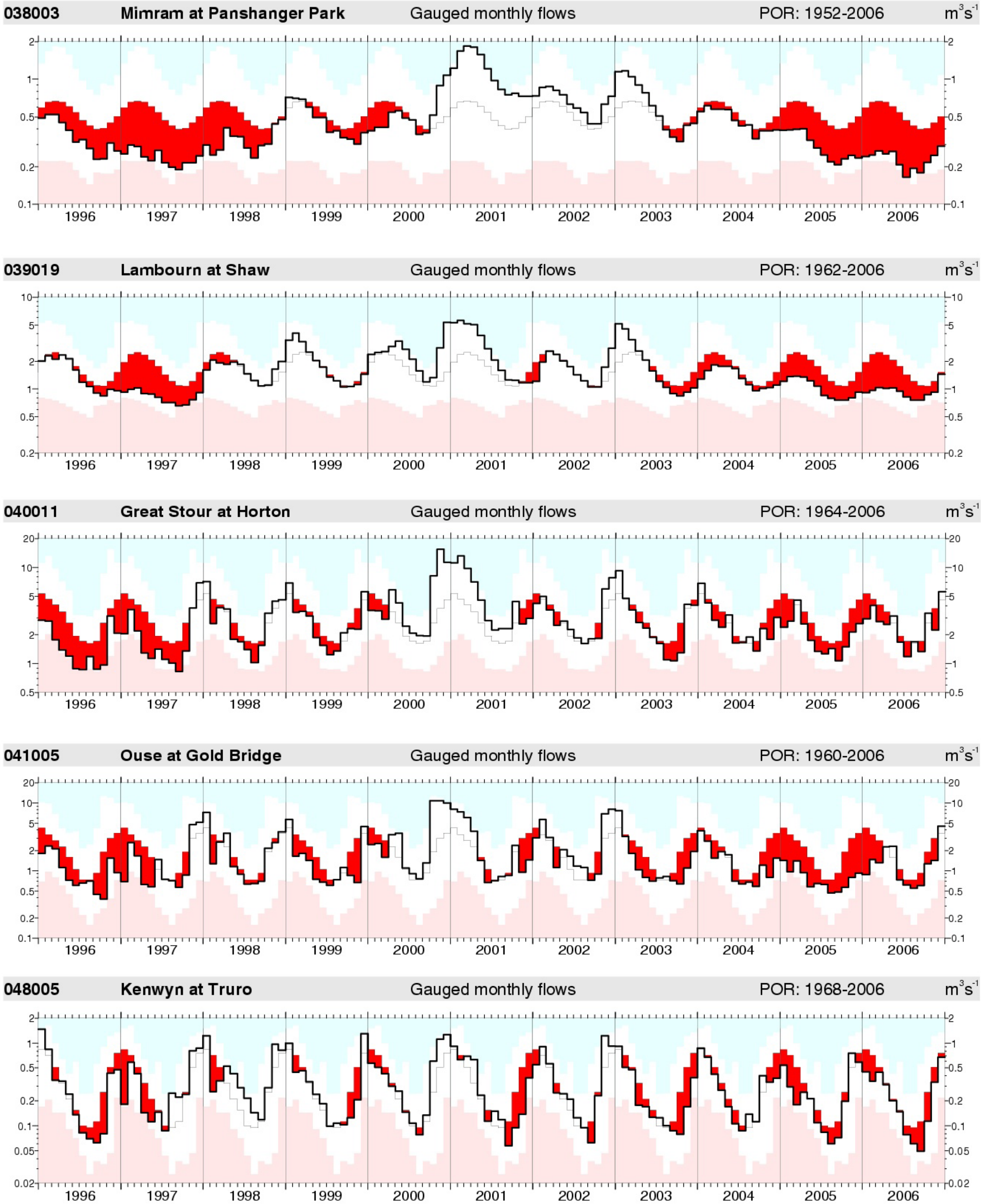


Figure 6 Monthly river flow hydrographs

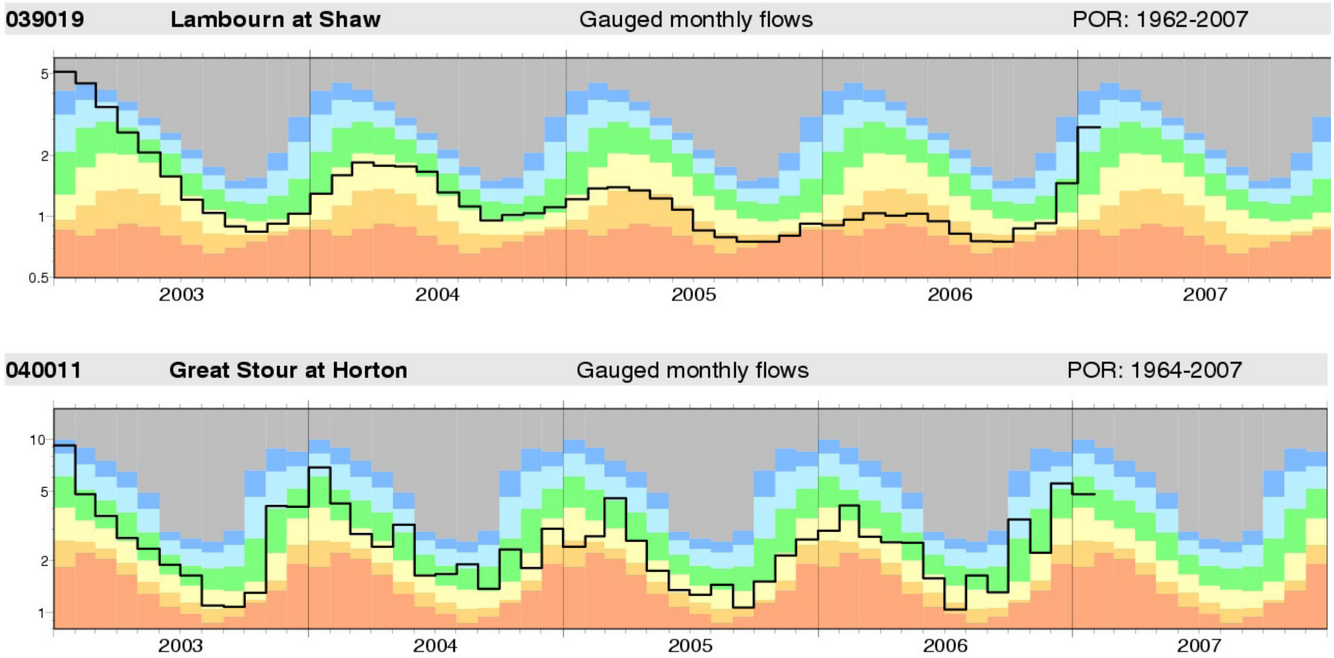


Figure 7 Monthly river flow hydrographs 2002-2007

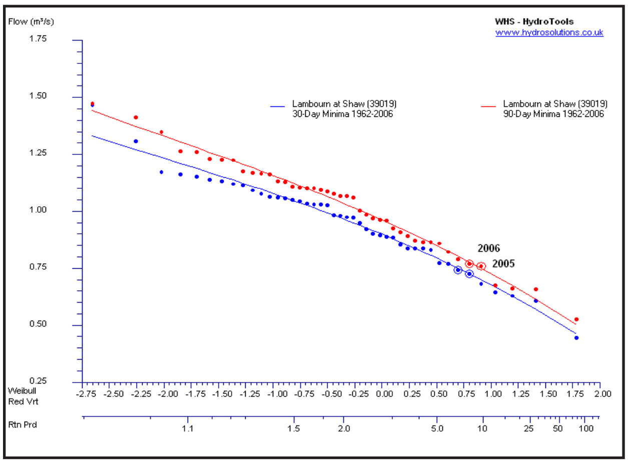


Figure 8   Flow frequency diagram for the River Lambourn in Berkshire

Figure 6 illustrates monthly river flow patterns for a selection of rivers in central and southern England since 1995. The periods of below average flow are emphasized by the red shading; the logarithmic scale also gives greater prominence to the low flow range. Figure 7 allows the development and decay of the drought to be tracked in more detail. Monthly flows for the Lambourn and Great Stour are overlain on flow bands corresponding to those given on Figure 5; monthly flows which extend into the grey (high) and orange (low) envelopes have return periods in excess of 20 years.

In impermeable southern catchments river flows were, typically, more seasonally depressed in 2005 than in 2006 when short-lived spates in the late summer helped to maintain runoff rates above drought minima. The drought's impact was generally more evident in spring-fed streams and rivers. In permeable catchments monthly flows remained below average for very extended periods (over three and a half years in the case of the Lambourn) and closely approached long term minima in the final stages of the drought. For the Mimram, the September flow in 2006 was the lowest in a series from 1953. Similarly depressed flows characterized many spring-fed streams in the English Lowlands, and the associated contraction in the stream network was broadly comparable to that experienced in the early autumn of 1992 and 1997. Artificial flow enhancement (e.g. by groundwater augmentation or river regulation) helped to moderate low flows in some stressed areas of southern England particularly. However, even in rivers with near-natural regimes flows in 2005 and 2006 generally remained above drought minima. Figure 8 features flow frequency plots (annual 30- and 90-day minima) for the River Lambourn in the Berkshire Downs and Table 3 provides return period estimates for long duration n-day minima in 2005 and 2006 for five index rivers. The return periods for the 2005 and 2006 minima are generally moderate; the most notable being the 90-day minimum in 2005 on the River Itchen. Many of the minimum flows registered during the 2004-06 drought were similar to those associated with the 1989 and 1997 droughts; except for a few spring-fed streams and rivers, the 1976 minima were much more extreme. Table 4 ranks annual 7-day minimum flows and confirms that only in a few cases (e.g the Mimram) were the short-term flow minima experienced during the 2004-06 drought of an extreme magnitude, again most exceed the corresponding minima for 1976 by a significant margin.

Table 3 Return periods of long duration daily minimum flows

2005	***Lambourn***		***Gt Stour***		***Itchen***		***Soar***		***Taw***	
N-day	*Ann. Min.*	*RP*	*Ann. Min.*	*RP*	*Ann. Min.*	*RP*	*Ann. Min.*	*RP*	*Ann. Min.*	*RP*
30	0.726	7.9	1.001	5.3	2.643	12.5	0.302	2.6	1.658	1.9
90	0.760	9.0	1.217	4.0	2.746	15.2	0.378	2.4	2.446	2.4
180	0.807	9.5	1.360	5.6	3.071	13.7	0.405	5.5	4.674	2.8

2006	***Lambourn***		***Gt Stour***		***Itchen***		***Soar***		***Taw***	
N-day	*Ann. Min.*	*RP*	*Ann. Min.*	*RP*	*Ann. Min.*	*RP*	*Ann. Min.*	*RP*	*Ann. Min.*	*RP*
30	0.741	7.1	1.131	3.3	2.870	5.9	0.223	9.5	0.881	7.8
90	0.771	8.3	1.404	2.3	2.946	7.8	0.297	6.9	1.108	9.6
180	0.841	7.5	1.873	1.7	3.453	4.7	0.622	1.6	5.089	2.4

RP = return period

Table 4 Annual 7-day minima

River Mimram at Panshangar Park Record: 1952-2006

	7-day min. (Cumecs)	*% of lta*	*End date*
1	0.139	25.7	23/08/1976
2	**0.152**	**28.1**	**11/08/2006**
3	0.158	29.3	14/09/1973
4	0.165	30.6	22/08/1997
5	0.175	32.4	27/05/1992
6	0.18	33.3	03/01/1974
7	0.186	34.4	04/09/1991
8	**0.188**	**34.8**	**26/09/2005**
9	0.209	38.7	24/09/1965
10	0.212	39.3	22/08/1998

River Itchen at Highbridge/Allbrook Record: 1958-2006

	7-day min. (Cumecs)	*% of lta*	*End date*
1	2.209	40.6	26/08/1976
3	2.449	45.0	05/08/1992
3	2.496	45.9	22/10/1959
4	**2.550**	**46.9**	**22/07/2005**
5	2.581	47.5	15/09/1973
6	2.593	47.7	09/08/1989
7	2.609	48.0	18/09/1997
8	**2.655**	**48.8**	**12/09/2006**
9	2.660	48.9	17/09/1990
10	2.787	51.3	13/09/1991

River Lambourn at Shaw Record: 1962-2006

	7-day min. (Cumecs)	*% of lta*	*End date*
1	0.418	24.0	22/08/1976
3	0.570	32.7	07/08/1992
3	0.580	33.2	18/08/1965
4	0.618	35.4	18/10/1990
5	0.633	36.3	05/10/1997
6	**0.704**	**40.3**	**17/10/2005**
7	**0.705**	**40.4**	**12/09/2006**
8	0.721	41.3	15/10/1989
9	0.739	42.3	28/10/1991
10	0.786	45.0	25/11/1964

River Lymington at Brokenhurs Record: 1960-2006

	7-day min. (Cumecs)	*% of lta*	*End date*
1	0.007	0.67	03/08/1962
3	0.007	0.67	23/08/1976
3	0.013	1.24	12/08/1990
4	0.016	1.52	07/08/1992
5	0.018	1.71	09/08/1995
6	0.020	1.90	15/09/1991
7	0.021	2.00	08/08/1989
8	0.026	2.47	23/08/1984
9	**0.030**	**2.85**	**14/08/2006**
10	0.032	3.04	08/08/1996

Reservoir stocks

Over the 1998-2002 period, reservoir stocks across England and Wales remained very healthy but declined steeply through the intense spring and summer drought of 2003. Stocks generally recovered in 2004 and, despite the drought conditions over the succeeding two years, they remained mostly well within the normal range at the national scale. Figure 9 provides an index of overall reservoir stocks based on a network of major impoundments across England and Wales. This confirms the health of overall stocks through most of the drought period but a relatively steep decline through the spring and summer of 2006 left early August stocks at their lowest for a decade, but still within 5% of the late summer average.

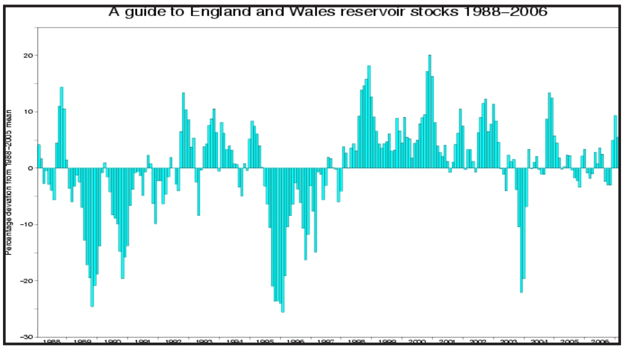


Figure 9 A guide to overall reservoir stocks in England and Wales

The limited depletion at the national scale masks the degree of water resources stress evident in parts of southern Britain where the impact of the developing drought on reservoir stocks is much more evident. Figure 10 shows 2004 (blue trace), 2005 (red) and 2006 (black) monthly reservoir stocks for Bewl Water (on the Kent/Sussex border) and Colliford (Cornwall). For the former, stocks remained reasonably healthy until the summer of 2005. Thereafter, the absence of any appreciable seasonal recovery left stocks at their lowest on record entering 2006. Aided by a wet late spring and Drought Permits allowing additional pumping from the River Medway, stocks at Bewl Reservoir recovered briskly. Summer stocks were considerably higher than in 2005; a situation replicated throughout much of the drought-affected region but there were important exceptions. In parts of the South West stocks remained seasonally depressed, particularly in Cornwall where Stithians and Colliford reservoirs declined to below 50% of capacity in the late summer.

Stocks continued to decline into the late autumn of 2006 and at year-end Colliford was only marginally above half full – a reflection of a long term rainfall deficiency (since 2001) and a small catchment area relative to the reservoir's capacity, implying that post-drought recoveries could extend over several years.

Depleted resources triggered the introduction a range of other drought mitigation measures (e.g. publicity campaigns to moderate demand, local water transfers, reductions in compensation flows and temporary switching of depleted reservoirs to non-consumptive mode). Sutton and East Surrey Water introduced a hosepipe ban in the late spring of 2005. A year later, with groundwater resources seasonally depressed over wide areas, water use restrictions were extended across much of the South-East, affecting over 13 million consumers in total. Stocks in the major-pumped storage reservoirs which service London's needs can decline rapidly through the summer but, aided by reduced demand, they held up well in 2006. With most gathering grounds close to saturation by the late autumn, gravity-fed reservoirs reported healthy replenishment from mid-October and, generally, stocks were in the normal range by early January 2007.

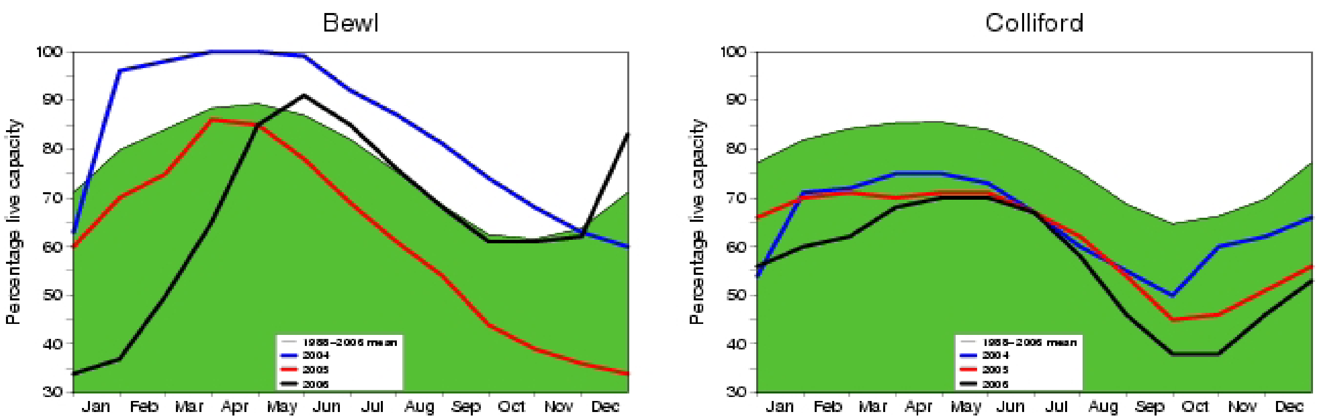


Figure 10 Variations in monthly stocks for the Bewl and Colliford reservoirs

Groundwater resources

The drought achieved its most extreme expression in relation to groundwater resources in parts of the English Lowlands. In groundwater terms, the drought's development can be seen, in part, as a legacy of the arid conditions experienced throughout much of 2003. Exceptionally dry autumn soils substantially delayed the seasonal onset of aquifer recharge and (notwithstanding the above average November-April rainfall) aquifer replenishment over much of the English Lowlands was insufficient to return groundwater levels to their normal spring maxima in 2004.

From the autumn of 2004 to the winter of 2006, the spatial and temporal distribution of rainfall was very unhelpful from a groundwater perspective[5]. Winter and spring rainfall was well below average across most major aquifer outcrops and the seasonally dry soil conditions (a consequence of above average evaporative demands) again served to restrict the length of the recharge seasons. The 2004-06 period provides a very clear demonstration of the sensitivity of aquifer recharge to changes in winter half-year rainfall and the consequent vulnerability of groundwater resources to clusters of dry winters. Figure 11 plots the relationship between October-March rainfall and Effective Precipitation totals for the westerm Chilterns. Winter half-year rainfall totals of less than 250 mm can be expected to generate very meagre recharge and a 30% deficiency in rainfall translates into a recharge deficiency of around 60%. Estimated EP totals for the October-March periods in both 2004/05 and 2005/06 were below 35% of average. The effect of the paucity of recharge is illustrated in Figure 12 which features 1996-2006 groundwater level hydrographs for five index wells and boreholes in England. For the Chilterns (represented by the Stonor borehole), the residual benefit of exceptionally high groundwater levels in early 2003 is still evident in 2004 but the weakness of the subsequent seasonal recoveries left levels approaching long term minima by the early autumn of 2006. As in other Chalk outcrops, the degree of water-table depression would have been more severe without a seasonally late pulse of recharge in April and May which moderated groundwater level recessions (and briefly reversed them in a few areas). A broadly similar recharge pattern is evident in the slow-responding Permo-Triassic sandstones of the Midlands where groundwater levels reflect recharge patterns over a number of years. At Heathlanes, barely an inflection in the recession can be recognised over the 2004-06 period and, by the autumn of 2006, groundwater levels had fallen below all but the minima recorded in the final phase of the 1995-97 drought.

The wells featured in Figure 12 are located in outcrops where the drought achieved its greatest severity. Away from these aquifer units, the depletion of groundwater resources was generally much more moderate. Levels in most limestone aquifers remained within the normal range and the drought's impact on minor aquifers (e.g. in Norfolk) was limited. Figure 13 maps September 2006 groundwater levels for a network of index wells and boreholes across the UK. It serves to emphasise the large regional and more local variations in the degree of water-table depression which characterised much of the 2004-2006 drought. Even within the Chalk aquifer, the degree of resource depletion varied substantially with relatively healthy resources in the more northerly outcrops.

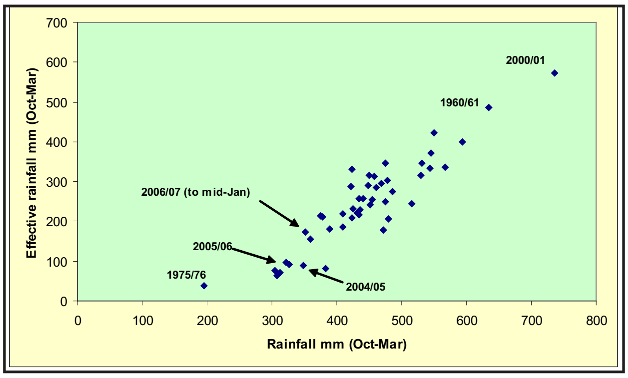


Figure 11 The relation between winter half-year rainfall and effective precipitation in the Chilterns

Figure 14 allows the drought's impact on overall storage in the Chalk to be considered in the context of groundwater resource variability over the last 37 years. The limited spatial extend of the most severely depressed water-tables in 2004-06 is confirmed by the lesser magnitude of the resource depletion relative to the protracted groundwater droughts of the early and mid-1990s. On limited evidence, the 1990-92 groundwater drought was probably the most severe in England and Wales for more than 80 years[6,7].

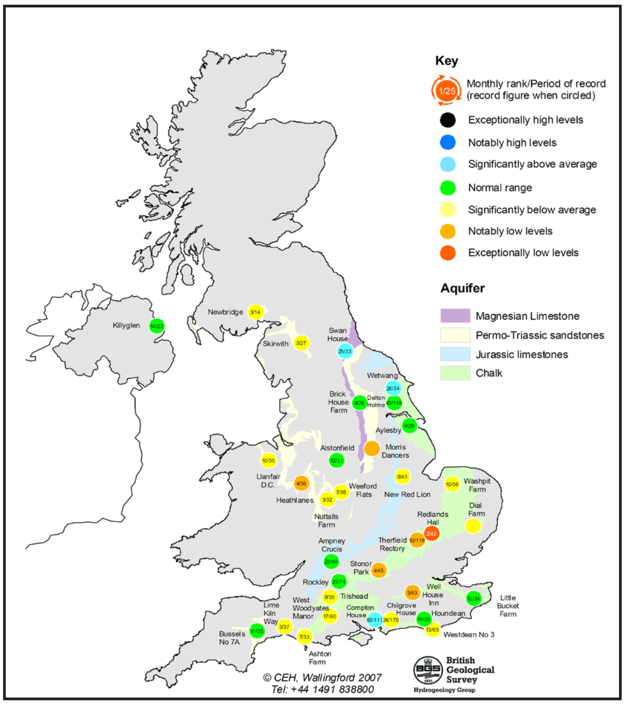


Figure 13 Ranking of September 2006 groundwater levels for a network of index wells and boreholes

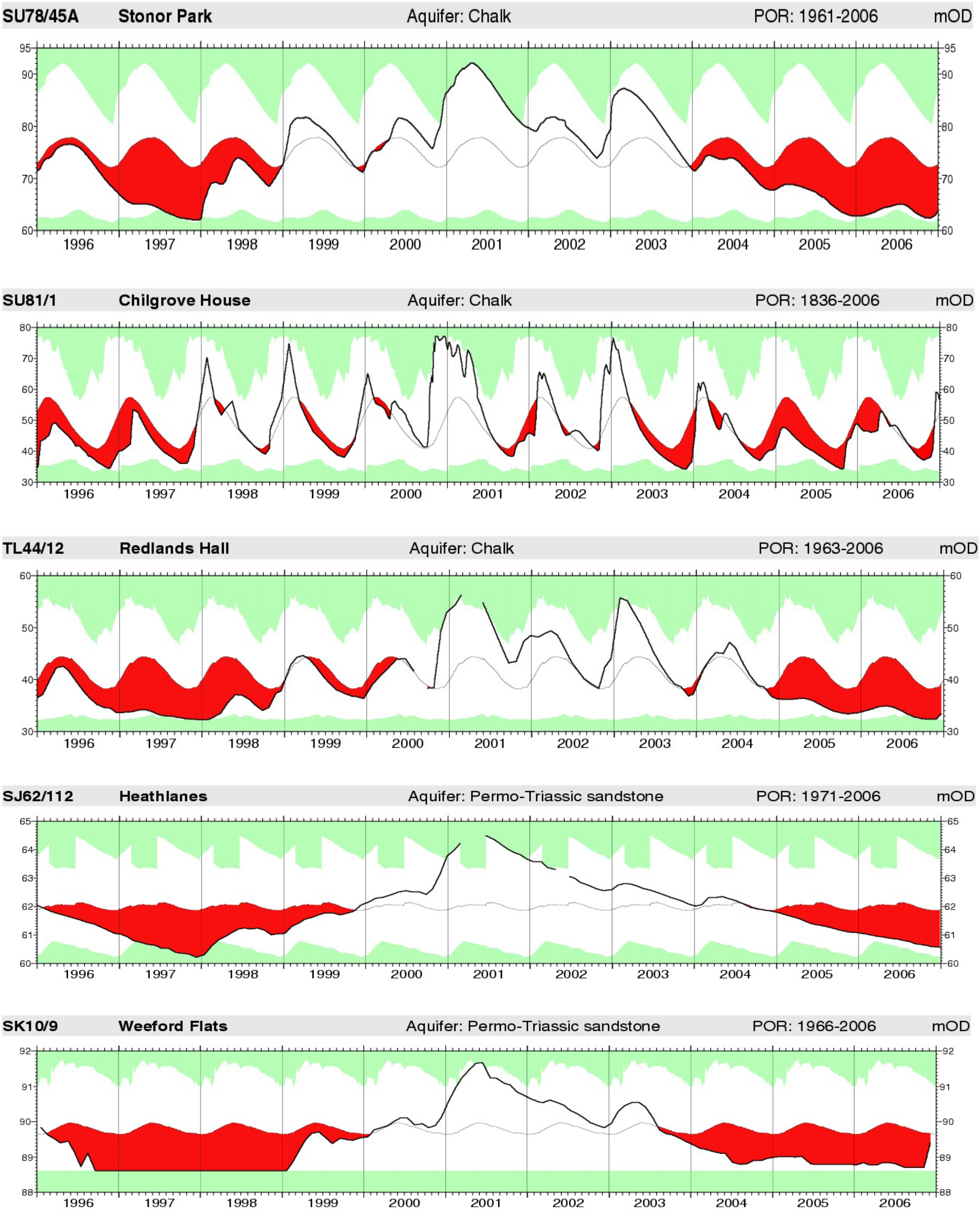


Figure 12 Groundwater level hydrographs

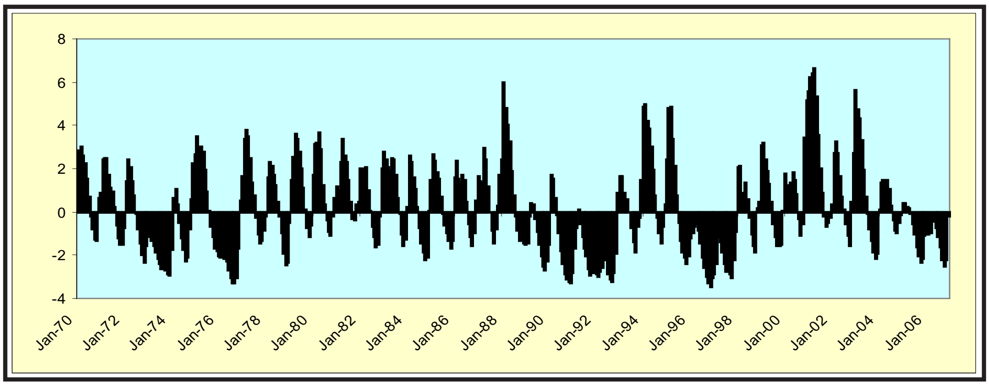


Figure 14 An index of total storage in the Chalk aquifer, 1970-2006

Hydro-ecological impacts

Many factors influence the health of river ecosystems including temperature, oxygen, light and discharge. All elements of the flow regime are important, including floods, average and low flows. Depressed groundwater levels and the associated widespread failure of springs contributed to very sustained low flows and a major contraction in the lowland stream network over the 2004-06 period (see Plate 1). The lack of spates and drying up of headwater tributaries represented a particular risk to migratory fish that require sufficient flow to trigger upstream movement and to reach their spawning grounds. Limited inflows (from surface or groundwater) and exceptional evaporation demands led to many ponds drying up and fish rescues were needed as water levels became critically low. Low oxygen levels were an exacerbating factor in some water bodies but oxygen concentrations remained relatively healthy in most spring-fed streams. Encouragingly also, a CEH sampling programme on Chalk streams in Berkshire and Dorset revealed no major drought impacts on the freshwater invertebrate population structure during the summer of 2006[8].

The lack of spates and drying up of headwater tributaries represented a particular risk to migratory fish that require sufficient flow to trigger upstream movement and to reach their spawning grounds. Although it is difficult to predict the effects of droughts on fish populations it is possible to estimate how low flows change the amount of suitable habitat available for certain species[9]. Flow in the river interacts with channel morphology to create the patterns of depth, velocity and width that freshwater communities utilise. Prolonged periods of low flow can have adverse affects on river health through a lack of dilution and by altering the physical conditions in the river. During periods of low flow less wetted area may be available, depths may be shallower and velocities slower. This can be a particular problem for young salmonid fish, which prefer moderate velocities and avoid very shallow water whilst drift-feeding.

Figure 15 shows that during the prolonged low flow period in the summer of 2006 only around 5% of the River Lymington at Balmerlawn (Hampshire) provided conditions that were suitable for drift-feeding juvenile trout. During 2006 there was a prolonged period of limited availability of suitable drift-feeding trout habitat when compared to a more typical year such as 2004. However, conditions were not as bad as in the summer of 1976; the most severe drought on record at this site. Low flows during 2006 had a less damaging impact on habitat in more steadily flowing rivers such as the River Kennet (Berkshire) which, unlike the Lymington, relies primarily on groundwater to sustain summer flows. During 2006 the Kennet provided similar levels of habitat as was the case in 2004 (Figure 15), and the availability of suitable habitat far exceeded that of the summer of 1976 when flows were the lowest in a 45-year record. Flows recorded across southern England in 2006 suggest that the habitat loss was broadly similar to that which occurred during the summer/autumn droughts of 1992 and 1997.

Plate 1 The River Pang in Berkshire, August 2005

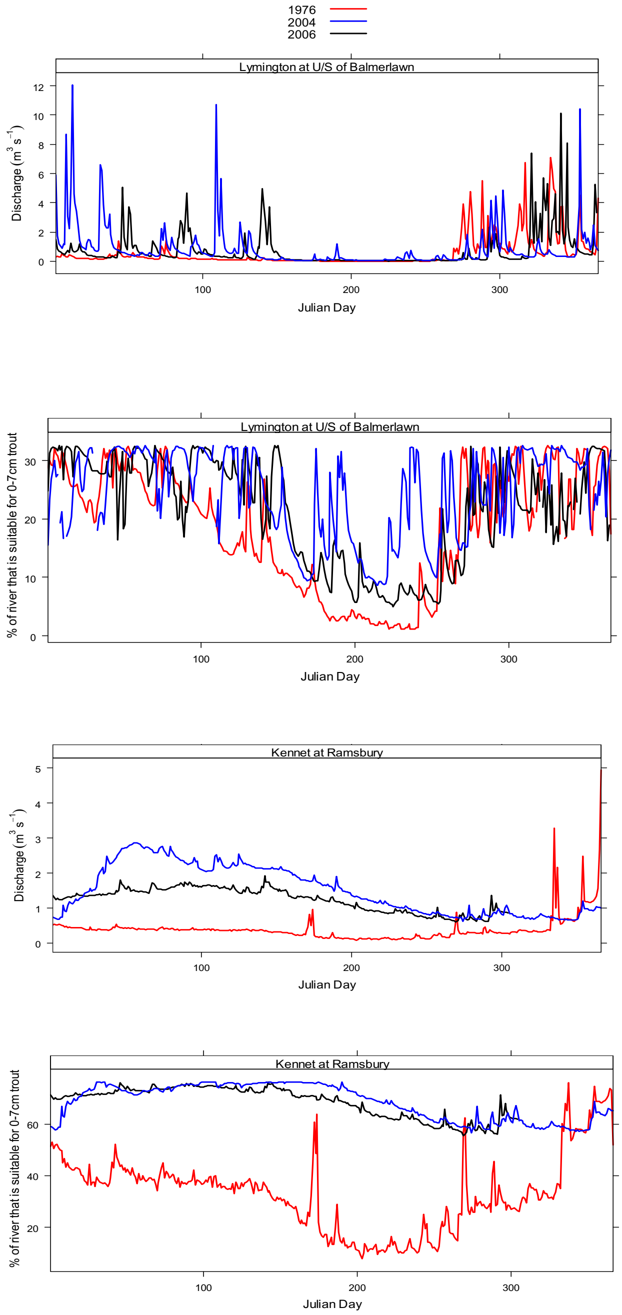


Figure 15 A comparison between habitat availability in selected years

The terminal phase of the 2004-06 drought

Drought termination can be a protracted process in the UK with wet interludes, particularly during the summer half-year, providing a temporary respite but having little immediate impact on water resources (aside from a reduction in water demand). On the other hand, some recent droughts (e.g. 1976, 1984, 1995) have ended dramatically as prolonged sequences of vigorous low pressure systems brought heavy rainfall extending over a number of months.

In 2006, convective storms in the late summer helped, locally, to moderate soil moisture deficits but a more general amelioration of the drought awaited the onset of persistent cyclonic conditions during an exceptionally mild autumn. A high frequency of active frontal systems continued into the early winter. England and Wales registered its 4th highest August-December rainfall in the last 52 years and most, but not all, of the drought affected regions registered substantially above average rainfall in this timeframe (see Figure 16). Rainfall was again very spatially variable with some areas reporting only average rainfall (e.g. the Isle of Wight) and, for a few catchments, overall rainfall deficiencies increased (e.g. in Cornwall).

Soil moisture deficits lingered into 2007 in a few areas close to the Wash but generally declined rapidly through October allowing runoff and recharge rates to recover smartly across much of the English Lowlands. River flows increased briskly through November in many impermeable catchments – most reporting above average flows by month-end. Flow response was characteristically more sluggish in spring-fed rivers but the onset of substantial aquifer recharge (see below) triggered a brisk recovery during the late autumn (see the Lambourn hydrograph, Figure 7). In December, moderate floodplain inundation was widely reported in mid-month and, by early January, the focus of hydrological stress had (in most areas) switched decisively to the risk of flooding.

Notwithstanding drawdown in some major reservoirs for flood alleviation purposes during the early winter of 2006/07, stocks increased briskly across almost all of the UK. For England and Wales as a whole the November/December increase was, marginally, the highest for any two-month period over the last 10 years. Entering 2007, most impoundments were close to capacity but there were several important exceptions in the South West.

Seasonal water-table recoveries in most western and northern aquifers gathered momentum in October and the elimination of soil moisture deficits across most of the English Lowlands triggered the most productive recharge episode for the Chalk in the last four years. This generated steep recoveries in the rapidly responding aquifers but more sluggish responses in core of the drought region. However, a very large pulse of recharge was descending through the unsaturated zone at year-end. Estimated EP totals for the October-mid January period strongly indicate that recharge in parts of the Chalk (e.g. the Chilterns) had already exceeded the combined replenishment for the full recharge seasons in 2004/05 and 2005/06. Recharge to the Permo-Triassic sandstones was abundant also but their characteristic very high storage implies that a full recovery, to above the seasonal average, may take several years.It should be stressed that the rainfall and recharge recoveries are not of a similar magnitude to those in 2002/03 which left groundwater resources in southern Britain sufficiently healthy to withstand the ensuing intense spring-autumn drought; rainfall over the February-October period was the lowest since 1921 for the UK. A dry late winter and early spring could lead to a rapid deterioration in the water resources outlook, as happened in 1990 and 1995[10] for example. This could have particularly severe consequences for some smaller impoundments, agricultural reservoirs and shallow groundwater resources in western and northern Britain. As usual, the length of the aquifer recharge season will be important in the drought-stressed aquifers; a wet spring to delay the onset on the seasonal recessions in groundwater levels would be particularly beneficial.

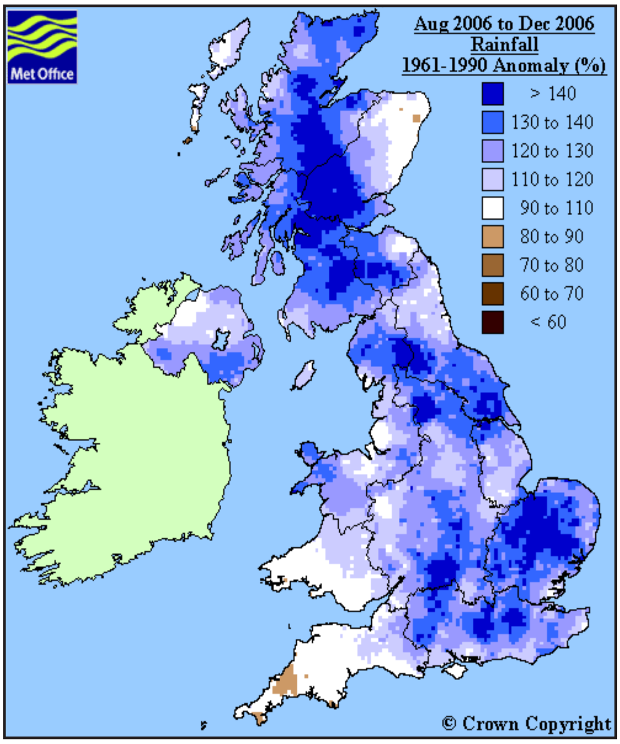


Figure 16 August 2006-December 2006 rainfall anomalies

The 2004-06 drought in context

By their nature, major droughts are rare events but any tendency for them to cluster or increase in magnitude or frequency has important ramifications for society and especially for water resources management.

The cluster of droughts in the recent past (1988-92, 1995-97, 2001 in northern Britain, 2003 and 2004-06) has increased speculation that climate change is already having an exacerbating influence on drought risk, in southern Britain especially. However, the contrasting characteristics of the two most recent drought episodes (see Table 5) emphasise the complexity of any association between drought duration and magnitude, and rising temperatures. An intense nationwide spring-autumn drought in 2003 has been followed by protracted drought conditions caused by a lack of winter/spring rainfall. The first is indicative of conditions that most favoured climate change scenarios suggest will occur with a greater frequency in a warmer world[11]. The latter event, however, is much less congruent with a future where an increased frequency of wet winters is anticipated. This may well reflect the inherent variability of the UK climate – which may become more capricious as temperatures rise.

The UK is blessed with an enviable legacy of climatological data which allows drought frequency to be examined over periods of 200 years or more. Annual rainfall totals for England and Wales exhibit no long term trend although perturbations about the long term mean can be substantial and protracted (see Figure 17). Some hydrometeorological time series exhibit a number of changes since the latter stages of the Little Ice Age in the early 19th century which have important implications for drought vulnerability. 2006 was the warmest year on record in the 337-year Central England Temperature Series and average temperatures are now around 1.2°C above those of a century ago.

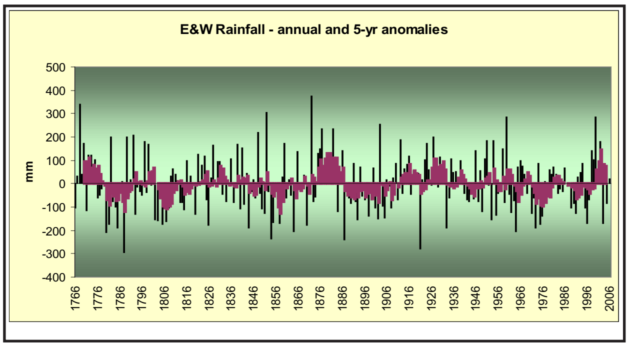


Figure 17 England and Wales rainfall anomalies 1776-2006

From a water resources perspective, a particularly notable contrast has been the change in the seasonal partitioning of annual rainfall totals over the last 200 years. For much of the 19th century, summer rainfall exceeded that for the winter and clusters of dry winters were common[4]. By comparison winter rainfall for England and Wales over the last 30 years has been around 10% above the previous average, and summer rainfall around 10% below. This tendency is consistent with most climate change scenarios[9] and implies a possible increase in runoff and groundwater recharge – a higher proportion of the annual rainfall occurring when evaporative demands are at their lowest.

Whilst the public perception of drought is linked more readily to hot dry summers, the 2004-06 drought underlines the primary importance of winter and spring rainfall, in the English Lowlands especially. Low winter rainfall during 1990-92 and 1995-97 had a severe impact on groundwater resources but sequences of dry winters have been relatively uncommon since the 1970s. This was not the case prior to the 1st World War when several lengthy sequences of dry winters may be identified (e.g. in the 1850s and during the 'Long Drought' of 1890-1910[4]). On the basis of incomplete evidence, the impact on groundwater resources and the aquatic environment was more severe than that experienced during contemporary drought episodes.

Table 5 General characteristics of the 2003 and 2004-06 droughts

2003 drought	2004-06 drought
UK-wide	Strong regional focus
Relatively even intensity	Large regional (and local) variations in intensity
Driest Feb-Oct for the UK since 1921	Protracted drought, 20-26 months
Lowest 7-month outflow from the UK (1961-2006)	Caused by a lack of winter rainfall
Record summer temperatures	Summer half-year rainfalls in the normal range
Very wet preceding winter	Major, but spatially uneven impact on water resources
Very healthy antecedent surface and groundwater resources	Substantial contraction in stream network
Limited drought impact on resources	Decisive termination in most areas
Incomplete termination	Stronger legislative framework
Consistent with climate change scenarios	Much less consistent with climate change scenarios

Concluding remarks

Society and water resource management systems adapt over time to the vagaries of the climate. Notwithstanding a large increase in water demand over the last 100 years, England and Wales is now considerably more resilient to drought stress than in the 19th century when droughts posed a real threat to lives and livelihoods. This resilience is built upon improvements in water management and more effective institutional, regulatory and legislative structures. Their benefits were well demonstrated in 2005 and 2006. However, with temperatures, water demand and the expectations of stakeholders (e.g. in relation to moderating drought impacts on the aquatic environment) continuing to rise, any repetition of the rainfall patterns which characterized several 19th century droughts – the Long Drought in particular - would represent a very considerable challenge to the water industry across England and Wales. The 2004-06 drought has demonstrated the need to focus attention not only on the potentially amplifying impacts of drier summers in a warming world, but also on extending our understanding of the mechanisms which influence long and medium term variations in rainfall patterns – in particular those factors that contribute to a clustering of dry winters.

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References

1. Wigley, T. M., Lough, T. M. & Jones, P. D. 1984. Spatial patterns of precipitation in England and Wales and a revised homogeneous England and Wales precipitation series. *Int Jour. Climatol.,* 1-27

2. Marsh, T.J. 2004. The UK Drought of 2003 – a hydrological review. *Weather,* Vol. 59, No. 8, 224-230

3. Manley, G. 1974 Central England Temperatures: monthly means 1659 to 1973. *Quart. Jour. Roy. Met. Soc*., 100, 389-405

4. Marsh, T. J., Cole, G. A. and Wilby, R. L. 2007. Major droughts in England and Wales, 1800-2006, *Weather* (In press)

5 Centre for Ecology and Hydrology/ British Geological Survey. 2006. H*ydrological summaries of the UK.* . CEH Wallingford

http://www.nerc-wallingford.ac.uk/ih/nrfa/monthly_summaries/archive.html

6. Marsh, T.J., Monkhouse, R.A., Arnell, N.W., Lees, M.L., Reynard, N.S. 1994. The 1988-92 Drought. *Hydrological data UK series*, Institute of Hydrology/British Geological Survey, Wallingford, 78 pages.

7. Bryant, S.J., Arnell, N.W. & Law, F.M. 1994. The 1988-92 Drought in its historical perspective. *Jour. IWEM*, 1994, 8**,** February 1994

8. Bass, J.A.B., Blackburn, J.H., Murphy, J.F., Kneebone, N., Gunn, R.J.M., Jones, E. 2007. The 2006 drought; preliminary assessment of impacts on macro-invertebrates in the Frome, Kennet and Lambourn. Centre for Ecology and Hydrology, Winfrith

9. Elliot, C. R. N., Dunbar, M. J., Gowing, I. and Acreman, M. C. 1999. A habitat approach to the management of groundwater dominated rivers *Hydrol. Process*. 13, 459-475

10. Marsh, T.J. 1996. The 1995 drought – evidence for climatic instability. *Jour. ICE Water Maritime and Energy,* 118, September 1996, 189-195

11. Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R. and Hill, S.UKCIP. 2002. Climate change scenarios for the United Kingdom. 120 pages

Location Map