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The impact of climate change on severe droughts

Major droughts in England and Wales from 1800 and evidence of impact

Science Report: SC040068/SR1

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SCHO1206BLSM-E-P

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Steve Killeen Head of Science

Executive Summary

This report presents work completed by the Centre for Ecology and Hydrology (CEH) as part of a study funded by the Environment Agency (Science Project SC040068) on the 'Impact of climate change on severe droughts: implications for decision making'. The aim of this project was to assess the implications of severe droughts for the water resources of England and Wales, based on case studies from the Anglian and North West Regions.

The report catalogues drought events and provides documentary evidence of their impact in the UK since 1800. It includes a preliminary assessment of relative severity, based on a range of hydro-meteorological data, including extended rainfall, river-flow and groundwater time series, an aridity index, and rainfall and runoff deficiencies over various time periods. The report also examines the rather patchy documentary evidence for drought pre-1800.

It is clear that throughout the historical record, drought has been a recurring feature of the UK climate, with recent drought events by no means exceptional in terms of their intensity or duration. A notable feature is the repeated tendency for dry years to cluster together, which results in multi-year droughts that contain shorter more intense periods. The extended drought periods from 1780-1790, 1798-1808, 1854-1860, 1890-1909, 1990-1992, 1995-1997 are all evidence of this. As many of these protracted clusters predate most observed river flow and groundwater time series, there is a clear danger that contemporary data sets (post 1950) may be unrepresentative of the full historical series. In particular, they do not capture the hydrological impact of the sequences of dry winters that are a feature of the pre-1920 rainfall series. Thus, drought risk (particularly in relation to protracted events) may be underestimated, although recent advances in drought mitigation, planning and infrastructure mean that many regions of the UK are now better able to cope with extended rainfall deficiencies than they were in the past.

When examining drought in an historical context we must also be aware of possible changes in climatic variability over the historical record, the changing ability of a region to cope with drought and the decrease in documentary evidence the further back in time. Extended rainfall records, supported by available long-term river flow and groundwater level time series, revealed no compelling trend of increasing drought frequency, although in eastern England summer rainfall appears to be decreasing. This clearly requires more thorough examination, which was outside the scope of the present study.

Contents

1. Introduction

This report outlines work completed by the Centre for Ecology and Hydrology (CEH) in Wallingford, as part of a study funded by the Environment Agency (Science Project SC040068), led by the Climatic Research Unit (CRU), on the 'Impact of climate change on severe droughts: implications for decision making'. The project was commissioned to assess the implications of severe droughts for the water resources of England and Wales. A 'bottom-up approach' was adopted involving the deliberate construction of specific climate events (based on historical severe droughts with climate change modifications), followed by an assessment of their potential impact and identification of the possible management and/or adaptation measures to mitigate those impacts. This approach is complimentary to the more usual 'top-down' one in which scenarios of future climate are developed and the overall impact of possible future events assessed.

Droughts are complex and multifaceted, both in their meteorological character and range of impacts. Recent drought events have highlighted the UK's continuing vulnerability to drought. It is important, however, that these events are not viewed just in terms of recent flow records, but in the longer historical context over several centuries. This enables the natural variability of drought events and impacts to be fully characterised and understood.

This report presents a preliminary identification of major droughts since 1800 for England and Wales, for the Anglian and North West Regions and also for the two target catchments of the Ely Ouse (Anglian Region) and Eden (North West Region). The analysis presented is based on a range of hydro-meteorological data and includes river flow and groundwater time series back to 1800, reconstructed by the CRU and CEH using extended precipitation and temperature records. The report also examines and collates documentary evidence of drought and its impact from the present day back to the 1700s and provides a preliminary assessment of relative severity.

2. Characteristics of droughts in England and Wales

Droughts are multifaceted both in their meteorological character and range of impacts. While in broad terms the concept of drought is readily recognised by the public at large, translating this intuitive understanding into an objective procedure to index or assess drought severity is far from straightforward. In part this reflects the difficulties of quantifying a phenomenon that varies in its areal extent, duration and intensity, both regionally and locally.

Any comprehensive attempt to identify drought episodes and to index drought severity needs to address the different, if overlapping, impacts associated with:

- meteorological droughts (defined essentially on the basis of rainfall deficiency);
- hydrological droughts (in which accumulated deficiencies in runoff and aquifer recharge are of primary importance)
- agricultural droughts (in which the availability of soil water through the growing season is the critical factor).

In addition, contrasting hydrogeological characteristics, water resource management options and patterns of water usage can produce substantially different vulnerabilities within any given region.

The environmental and community impact of extended periods of rainfall deficiency will therefore be uneven across both time and space with, on occasion, only a tenuous link between recent rainfall amounts and the degree of drought stress. Hot weather and dry soils in spring and summer may generate heavy water demand, as in 1990, which can overstretch the water distribution system even though overall water resources may be relatively healthy. Conversely, a wet summer, as in 1973 or 1992 (Marsh *et al*., 1994), may suppress demand and moderate drought impact when surface and groundwater resources are very fragile. Drought stress on the aquatic environment (because of exceptionally low river flows and groundwater levels) may be considerable, but the scale of the stress may be substantially different in neighbouring catchments. In lowland England during the 2003 drought, depressed summer flows in rivers that drained impermeable catchments coexisted with seasonally average flows in rivers supported primarily by groundwater (Marsh, 2004). 100 years previously, the effect of such hydrogeological control on flow regimes assumed an extreme expression when water shortages were reported in the south east during the wettest summer half-year on record (groundwater levels remained exceptionally low well into the summer of 1903).

The vulnerability of England and Wales to drought impact has changed markedly with time, reflecting the changing balance between water supply and demand and the strategies in place to manage drought situations. In the 19th century severe droughts could constitute a very real threat to lives and livelihoods (through, for example, crop failures or the increased risk of water-borne diseases). Communities relied on a single or group of local sources for water and therefore had little opportunity to manage drought. Nowadays, the ever-increasing demand for water and the priority given to security of supply necessitate a complex and more flexible multi-source supply infrastructure. Water companies have a statutory requirement to submit detailed Drought Plans to the Environment Agency that outline operational steps to maintain water supplies during a drought while protecting the aquatic environment.

The changing vulnerability to drought is accompanied by significant climatological differences between drought episodes pre- and post- First World War, especially in the English Lowlands. *Figure 1* shows 5-year running mean plots for November–April ('winter') and May–October ('summer') rainfall for the East Midlands (EMID) rainfall series. The respective averages over the past 50 years are similar, but prior to around 1920 summer rainfall generally exceeded that for the winter – often by a considerable margin. Clusters of dry winters were common (e.g., in the 1850s, 1890s and through much of the 18th century). The limited hydrological effectiveness of such a partitioning of annual rainfall amounts meant that in the English Lowlands groundwater levels were often depressed for lengthy periods (creating what would be recognised today as substantial environmental stress) and water supply difficulties were common. On the other hand, the frequency of damp spring and summer periods meant that low winter rainfall was often not as strong a signal of potential water supply and, particularly, agricultural problems as it would be today. In terms of annual rainfall, the EMID rainfall was appreciably lower (around 7%) in the 20th century than in the 19th, but there is no compelling overall trend in the 280 year series.[1]

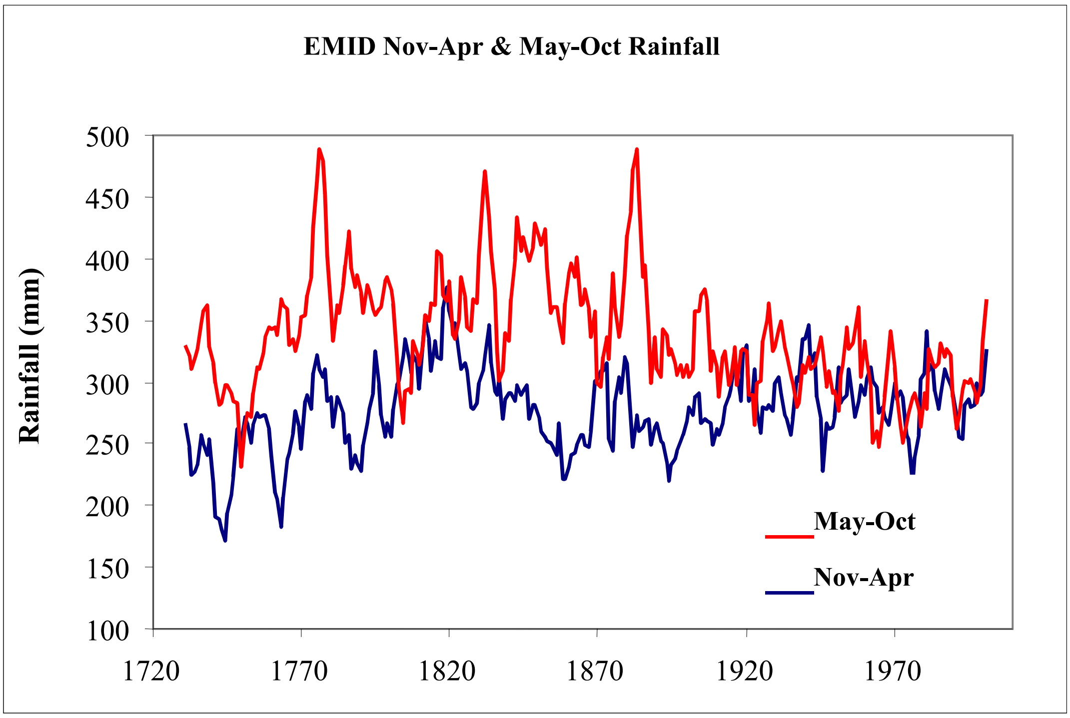


Figure 1: Comparison of long-term trends in summer and winter rainfall for East Midlands rainfall series.

[1] The homogeneity of the post-1960 EMID rainfall data is under review.

3. Identifying major droughts

No single methodology to assess drought severity is likely to reflect the full range of drought impacts, or readily factor in the changes in their relative importance over the past 200 years.

A simple guide to drought severity can be developed by combining rainfall and temperature information. *Figure 2* shows an aridity index for England and Wales based on the rainfall (homogenised EW series (CRU) from 1767) and temperature (Central England Temperature series, CET) anomalies for the summer half-year (April–September). As the equation below indicates, the anomalies have been normalised using the respective standard deviations (SDs) and weighted to give twice the influence to the rainfall deficiencies, as follows:

Aridity index = (Rainfall – Average rainfall)/SD rainfall + 0.5(Temp. – Average Temp.)/SD Temp.

where 'Rainfall' is the April–September total and 'Temp.' is the April–Sept CET. The 'Average' is the full record average in both cases.

This usefully identifies the most familiar recent summer droughts (e.g., 1995, 1976 and 1959), but has less utility for identifying winter droughts or very sustained periods of rainfall deficiency. The aridity index plot shows a greater frequency of notably arid summer half-years in the recent past than that 200 years ago. While there has been a long-term decline in summer half-year rainfall, this is primarily reflects the exceptionally high temperatures over the past 30 years.

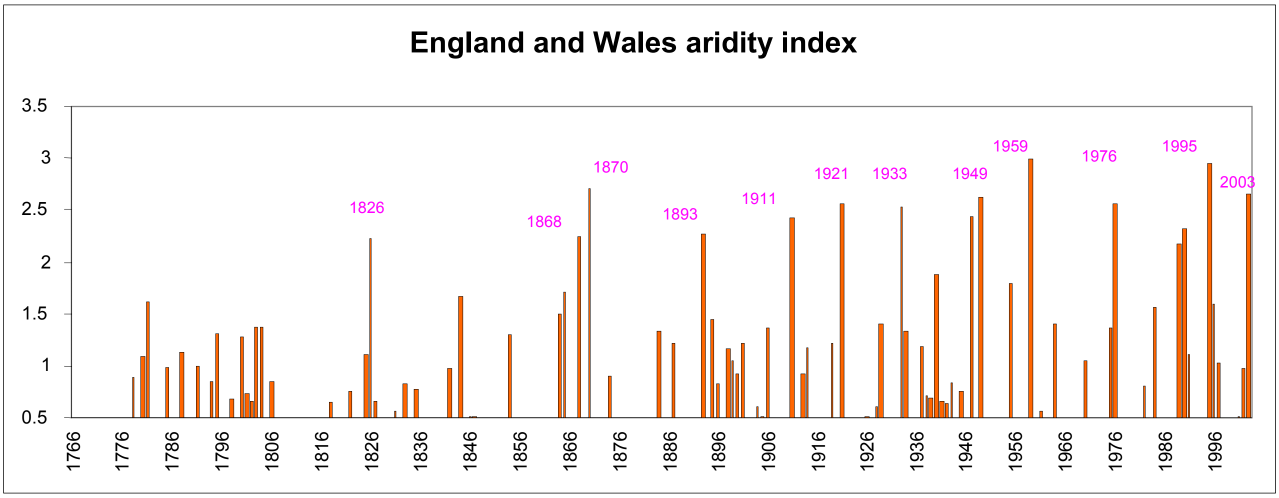


Figure 2: Aridity index (Marsh, 2004).

There is, however, little compelling evidence of any long-term increase in the frequency of very dry episodes for England and Wales. *Figure 3* shows the largest non-overlapping 12-month rainfall deficiencies for England and Wales; events featured are 12-month periods with rainfall totals of less than 770 mm. The cluster over the past 15 years is interesting, but the most exceptional events are distributed throughout the series (the sparse raingauge network prior to around 1850 implies a substantial uncertainty regarding the magnitude of the earliest drought events).

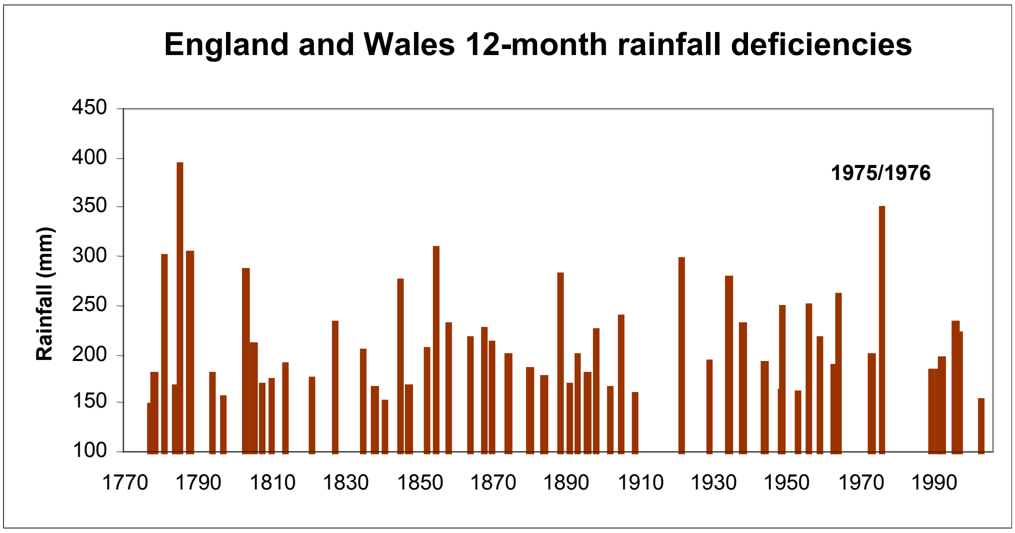


Figure 3: Largest non-overlapping 12-month rainfall deficiencies for England and Wales (from 1766).

Relatively simple indices based upon the accumulated deficiencies of monthly rainfall or runoff totals (e.g., Bryant *et al*., 1994; Mawdsley *et al*., 1994) can also be usefully indicative, but their application to particular regions (with particular water resource assets and management strategies) requires considerable care, particularly in the selection of realistic drought termination criteria. Changes in evaporative demands, both seasonally and over much longer time-spans, imply that runoff (or recharge) deficiencies are more appropriate for indexing drought severity in a water resources context. Unfortunately, few river-flow time series extend beyond 80 years – and none in the target regions for this study. Extended synthetic runoff series (Jones *et al*., 2004) provide a usefully indicative alternative – although possible changes in actual evaporation losses over the past 200 years (as implied by *Figure 1*) may result in an incomplete characterisation of runoff (pre-1930 especially).

For this study, the means of identifying significant drought episodes reflects both the preliminary nature of the first phase (identifying major drought episodes) and the availability of relevant hydrological time series and appropriate historical information. Two approaches have been used – the first based on hydroclimatological evidence, and the second using documentary evidence of drought impacts (see Section 4). For the hydroclimatological appraisal the following information was used:

- long-term monthly rainfall series held in association with the National River Flow Archive (NRFA), in particular the EMID and Central Lake District (CLD) series;

- long-term river- and spring-flow time series held on the NRFA;
- long-term groundwater level time series held on the National Groundwater Level Archive (British Hydrological Society, BHS);[2]
- extended monthly river-flow series derived by CRU for the Environment Agency contract;
- a simple aridity index (Marsh, 2004) based on the CET series and the 1766–2005 homogenised England and Wales rainfall series (to help identify the more severe summer drought episodes).

The resources available precluded detailed analysis of the hydro-meteorological time series. Selection of the more important drought events was, however, informed by the ranking position of dry winters and dry summers for two principal river-flow time series (the extended Ely Ouse and Eden datasets) and *n*-month minima analyses of rainfall and runoff. Visual appraisals of lengthy hydrological time series – plotted so that periods of rainfall or runoff deficiency are emphasised (see *Figures 4*,[3] *5*,[4] and *6*[4]) – and an aridity index (*Figure 2*) were also used to help identify the most significant drought events. Reference was made to the CET series to confirm documented assertions that relate to periods of outstandingly high temperatures.

The following sections present a preliminary identification of major drought events in England and Wales, and the Anglian and North West Regions (Section 3.1), and for the two target catchments upon which the water resources analyses will focus, the Ely Ouse and the Eden (Section 3.2). There are significant hydrological differences between the two regions. Average annual rainfall in north-west England exceeds 1200 mm and shows a distinct seasonality with the highest rainfall over the October–January period; on average evaporation losses comprise around 30-35 per cent of the annual rainfall. Most water supply in the North West Region comes from surface water resources, which makes the region particularly susceptible to short duration droughts (1-2 seasons). In contrast, average annual rainfall in the Anglian Region is less than 50 percent of that for north-west England (595 mm), and is also less seasonal. Annual potential evaporation losses can exceed rainfall totals and, correspondingly, mean runoff (and recharge) totals fall below 100 mm over wide areas. This, together with the large inter-year variability, implies a vulnerability to drought that is considerably greater than that in the wetter regions of the country.

[1] To provide flexibility, the analysis searched for the driest 5-month sequences that ended between January and May (‘winters’) and July and October (‘summers’).
[2] Extended groundwater series for Washpit Farm not available at the time of analysis.
[3] *Figure 4* shows monthly mean rainfall, with periods below average emphasised in red.
[4] *Figures 5* and *6* show monthly mean flows together with long-term average and envelopes that illustrate monthly maxima (green) and monthly minima (pink). Drought conditions (periods below average) are emphasised in red.

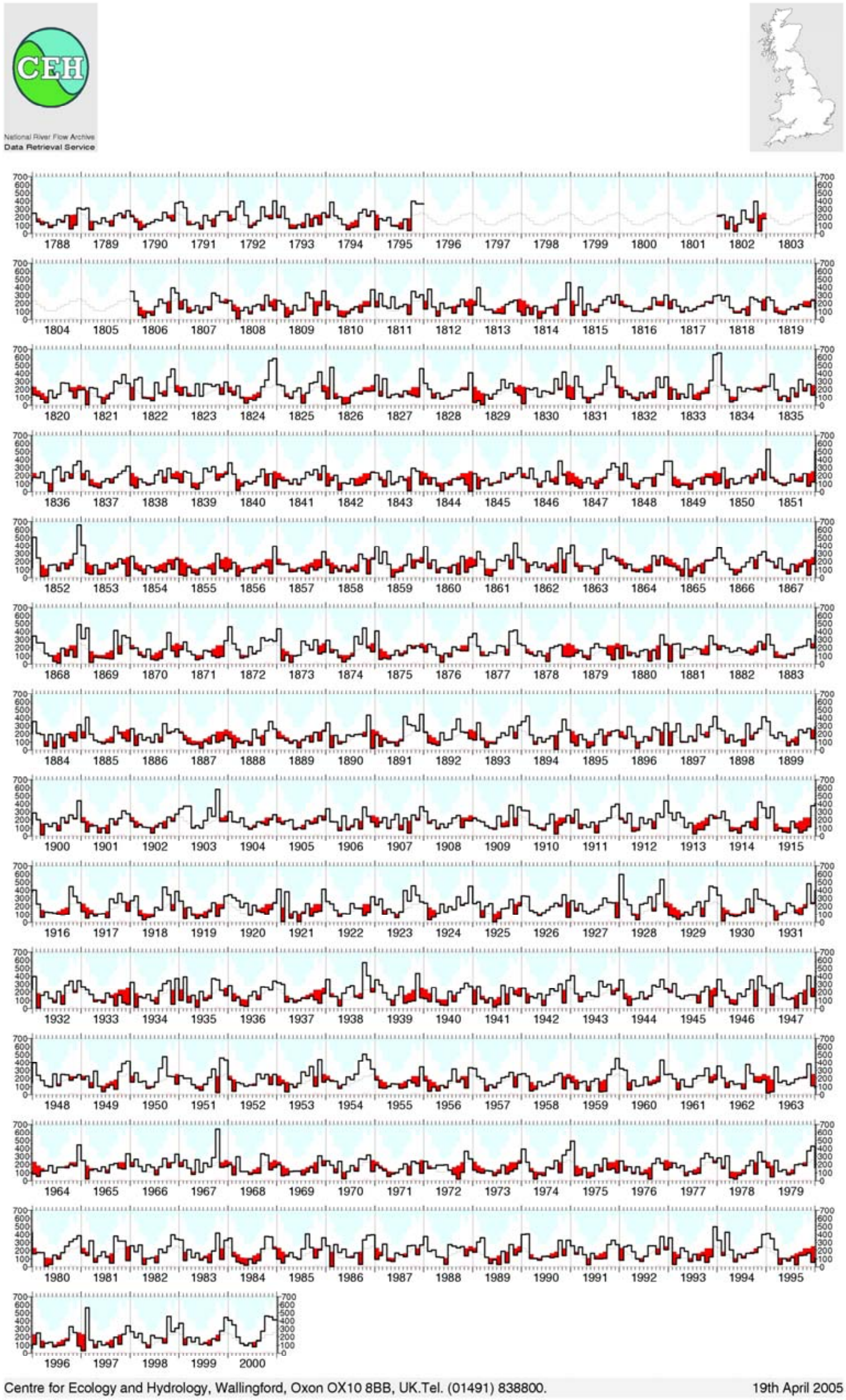


Figure 4: Example of long-term rainfall series for the Central Lake District used to identify drought episodes (Barker et al., 2004). [3]

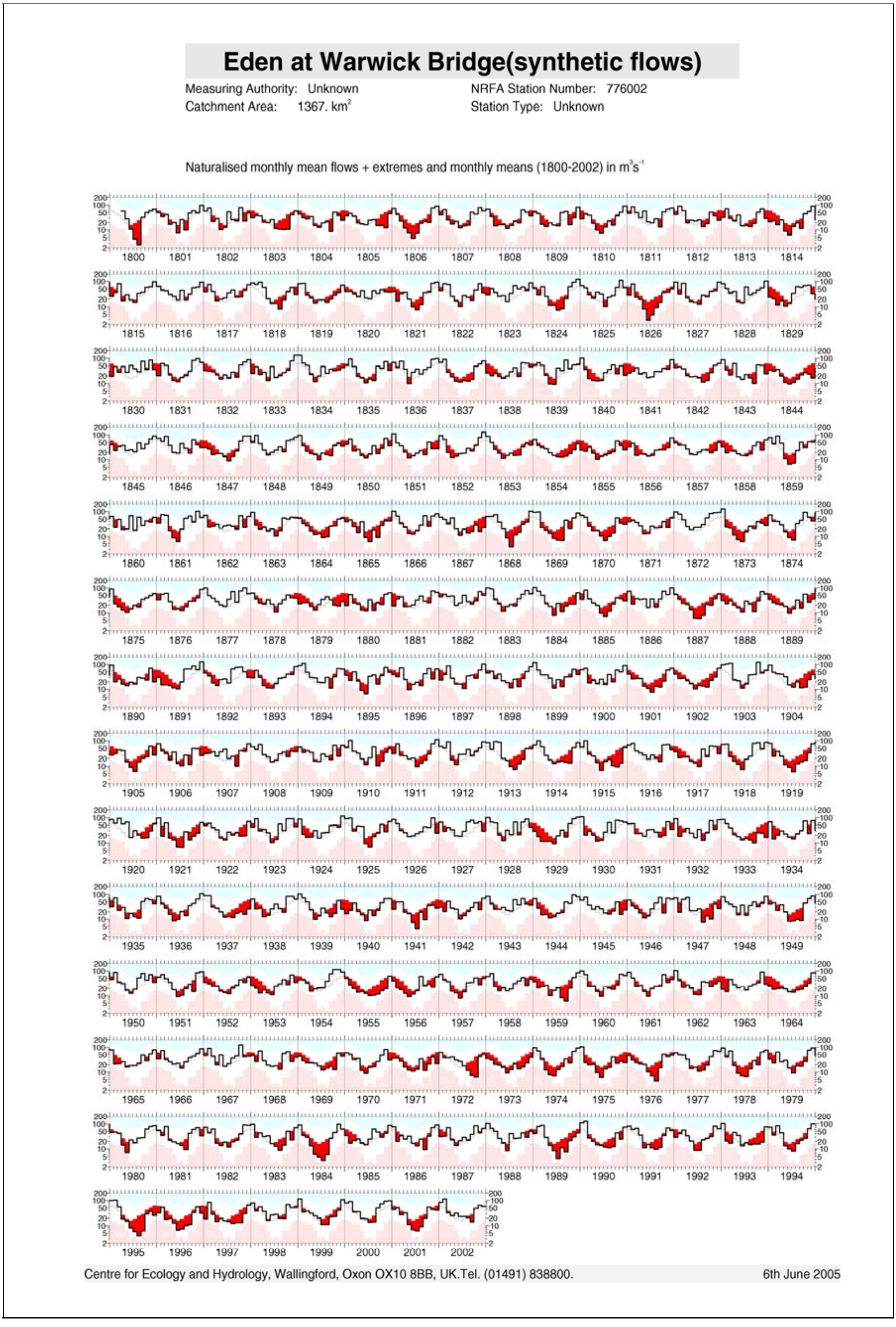


Figure 5: Long-term synthetic flow series for Eden at Warwick Bridge.[4]

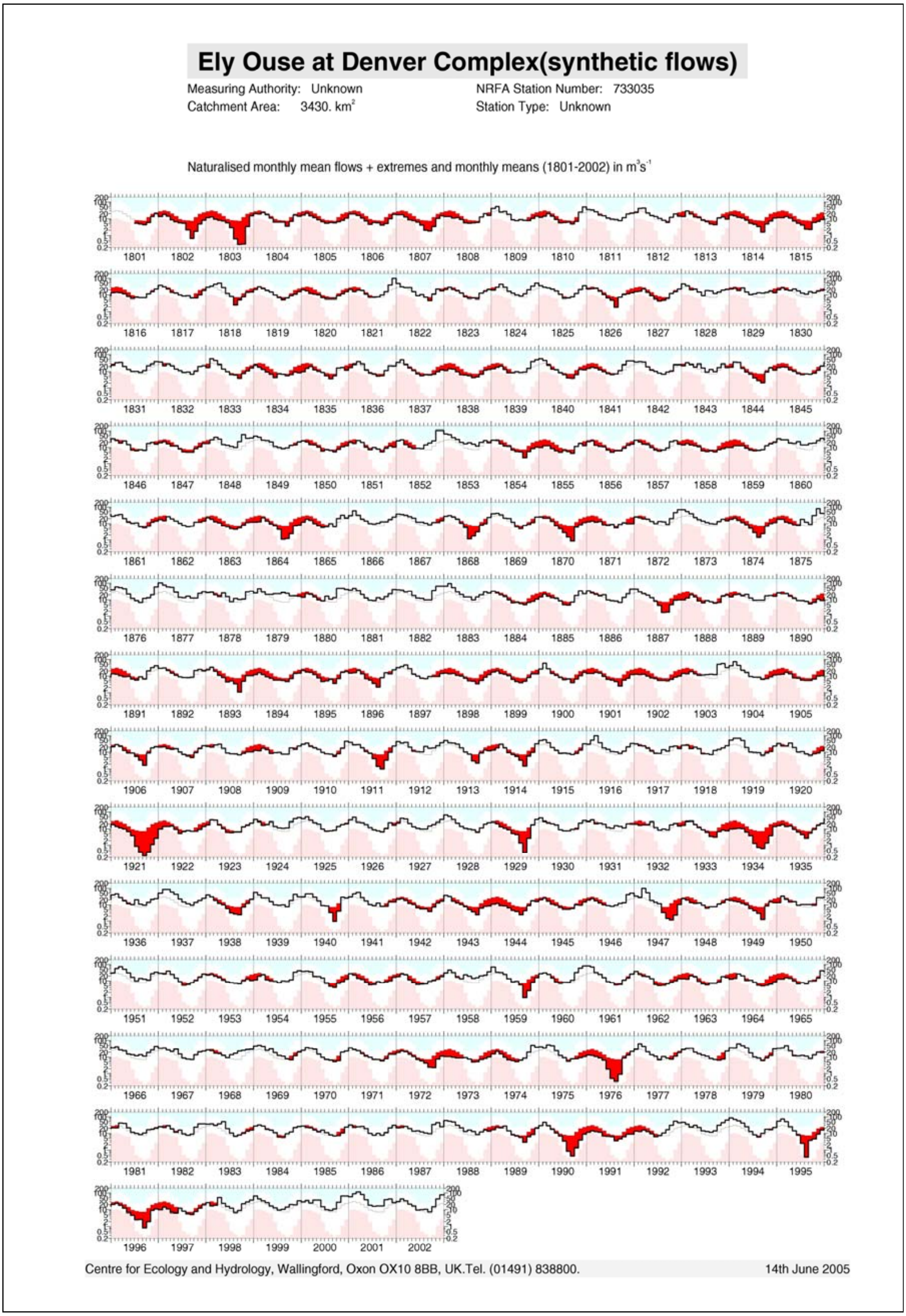


Figure 6: Long-term synthetic flow series for Ely Ouse at Denver.[4]

3.1 Major national and regional drought episodes

Appendix 1 lists notable drought episodes for England and Wales as a whole, together with separate entries for East Anglia and north-west England; shading is used to emphasise the major events. The hydro-meteorological evidence on which Appendix 1 was compiled is incomplete and varies in quality, both through time and between the regions featured. Judgement therefore needs to be exercised in assigning 'major drought' status to an event, especially those prior to 1920, when data were sparse. This becomes especially challenging when attempting to assess the relative severity of rainfall deficiencies of very long duration, compared with short but intense dry interludes. This is particularly significant given the greater frequency of very extended dry periods in the 19th century.

Table 1 has been compiled as a first attempt to summarise the most severe regional and national droughts from those listed in Appendix 1 (from 1800). Appendix 1 provides further information regarding the more intense episodes during the longest duration events (most of which were punctuated by very wet interludes) and an indication of whether surface or groundwater impacts predominated.

Table 1: Preliminary selection of major drought events.

England and Wales	*Anglian*	*North West*
1798-1808	1802-1803?	1854-1860
1854-1860	1854-1860	1869?
1887-1888	1873-1875	1887-1888
1890-1909	1890-1909	1915
1921-1922	1921-1922	1933-1934?
1933-1934	1933-1934	1976
1959	1959	1984
1976	1943-1944?	1995-1997
1990-1992	1976	
1995-1997	1990-1992	
	1995-1997	

Some events in *Table 1* are assigned a '?' to convey difficulties in fully assigning 'major' status to the event, because of its spatial and temporal variability. For example, the 1933-1934 drought increased in intensity from north to south across the North West Region and, in water supply terms, reflects the contribution from reservoirs in North Wales, where in 1934 the drought was particularly intense.

In general, the events in *Table 1* are in broad agreement with those identified by other authors using different selection criteria. Jones *et al*. (1997) use rainfall deficiencies to differentiate between short duration (8-10 months) droughts, which end in autumn and affect upland areas, and long duration (15-18 months), droughts, generally two summers and an intervening dry winter, that affect south eastern Britain. They identify the most severe short duration droughts since 1850 as 1887, 1921, 1929, 1959, 1984 and 1995, and long duration events as 1854-1855, 1869-1870, 1933-1934, 1975-1976 and 1989-1990, with 1921 and 1975-1976 the most severe in each category.

Jones and Lister (1998), using reconstructed river flows back to 1860 for 15 catchments across the UK, showed that although the 1990s had some of the lowest flows on record, there were earlier periods with more extreme 6 monthly river flows. They identified the most extreme events in the 20th century as 1921-1922, 1933-1934, 1975-1976 and 1984, with the 1989-1991 period unusual for the succession of three extreme years. All these events feature in *Table 1*. In a study of drought in Yorkshire, Fowler and Kilsby (2002) identify the worst 30 droughts (by season), using an index developed from the accumulated monthly precipitation deficit concept of Bryant *et al*. (1992). The 10 most severe events identified are shown in *Table 2*. The limited correlation with the North West Region events listed in *Table 1* is thought to reflect, in part at least, the constraints imposed by the fixed seasonal definitions employed by Fowler and Kilsby (2002).

Table 2: Ranked severity of drought events in Yorkshire (1881-1998) using the directional classification for 'western' water resource droughts (all years signify the start of the time period of drought – i.e., for winter (W) = October, and for summer (S) = April) (from Fowler and Kilsby, 2002).

Ranking	*Summer (S)*	*Winter (W)*	*W & S*	*S & W*	*S & W & S*
1	1887	1963	1886-1887	1887-1888	1887-1888
2	1921	1891	1887-1888	1968-1969	1894-1895
3	1984	1969	1946-1947	1955-1956	1995-1996
4	1893	1944	1958-1959	1894-1895	1968-1969
5	1884	1938	1894-1895	1995-1996	1886-1887
6	1968	1996	1995-1996	1941-1942	1884-1885
7	1955	1895	1943-1944	1885-1886	1895-1896
8	1976	1888	1895-1896	1896-1897	1885-1886
9	1959	1934	1910-1911	1921-1922	1893-1894
10	1896	1956	1940-1941	1947-1948	1983-1984

3.2 Major droughts in the Ouse and Eden basins

Table 1 and the appendices provide useful guidance in identifying or confirming drought episodes within the target basins (the Ely Ouse and Eden)' which are to be employed in the detailed examination of drought impacts on water resources. However, drought vulnerability in these basins is a function of the particular mix of surface water and groundwater available (and the management thereof). Droughts identified as significant at the national or regional scale may not present any severe water resources threat in the target basins – often because the intense phase of the drought does not correspond to the critical period for the contemporary water resources provision. Even major within-year rainfall deficiencies normally have only a limited impact in areas dependent on groundwater (this was clearly evident in 2003, for example), while intense rainfall deficiencies over 4-6 months can threaten water supplies in areas dependent on surface water storage (as happened in the northern England during the spring and summer of 1984 and 1995). It should be recognised also that spatial variations in drought intensity are often substantial and that regional designations of drought stress can obscure important contrasts between river basins. In the severe drought of 1959, for example, rainfall deficiencies in the coastal catchments of Norfolk and Suffolk were considerably greater than those that characterised the rest of East Anglia, the Ouse basin in particular (Wright, 1978).

As the size of target region diminishes, so the likely availability of documentary evidence of historical drought impacts also decreases and the indexing of drought severity, for the earliest events, becomes heavily dependent on rainfall data for one or two raingauges. Generally, lengthy rainfall time series have been subject to considerably scrutiny and can be considered acceptably homogeneous. However, they may not fully represent a catchment of interest – particularly where, as in the upper Eden, the altitude range is large. There is also the possibility of bias (underestimation) because snowfall contributed a higher proportion of the overall precipitation total in the early record.

To provide a consistent basis for drought identification in this study, the extended naturalised monthly flow series for the Ely Ouse (above Denver) and the Eden (above Warwick Bridge) have been used. For the initial analyses, non-overlapping minimum runoff totals for 18 months (the Ouse, see *Table 3*, *Figure 7*), and 6 and 12 months (the Eden, see *Table 4*, *Figure 8*) have been identified.

Table 3: **Maximum 18 month runoff deficiencies for the Ely Ouse at Denver (synthetic naturalised series 1801-2002)**

Rank	Runoff (mm)	% of long-term average	End month	Year
1	69.1	33.5	Nov	1803
2	80.5	39.0	Nov	1934
3	86.6	42.8	Oct	1922
4	90.1	43.7	Nov	1991
5	90.3	43.8	Nov	1815
6	94.7	46.8	Oct	1944
7	97.2	48.0	Oct	1997
8	100.7	49.7	Oct	1894
9	101.9	49.4	Nov	1973
10	103.5	50.2	Nov	1902
11	106.6	51.2	Sep	1855
12	107.4	51.6	Sep	1808
13	109.6	53.1	Nov	1976
14	112.1	53.9	Sep	1865
15	112.9	55.7	Oct	1871

Accepting the caveats given above, the exceptionally low (synthesised) runoff for the 18 month period ending in November 1803 is a striking feature of *Table 3* – both in itself and within the context of the sustained drought conditions, which continued, with brief wet interludes, until the end of the decade. Like the 1893-1905 period, this represents an important and under-documented drought episode. The maximum runoff deficiencies listed in *Table 3* generally correspond to the major or notable droughts featured in

Appendix 1 (for the Anglian Region and England and Wales). This was expected given the extensive and protracted nature of many of the major droughts. By contrast, *Table 4* exhibits less correspondence with the major national droughts and differs significantly even from those identified for the North West Region (see *Table 2*). A key factor here is the length of period over which runoff is accumulated to index drought severity.

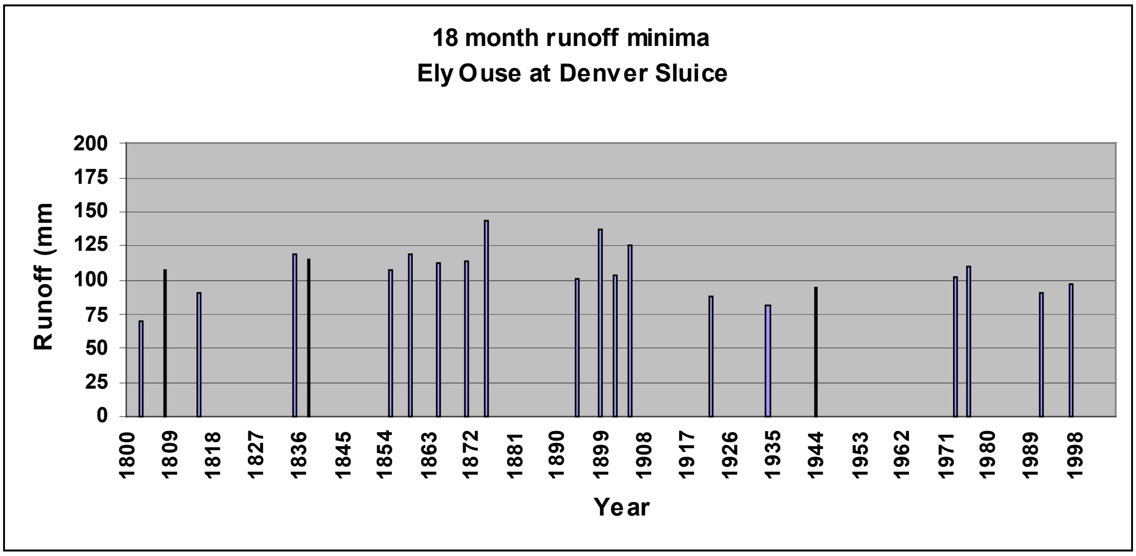


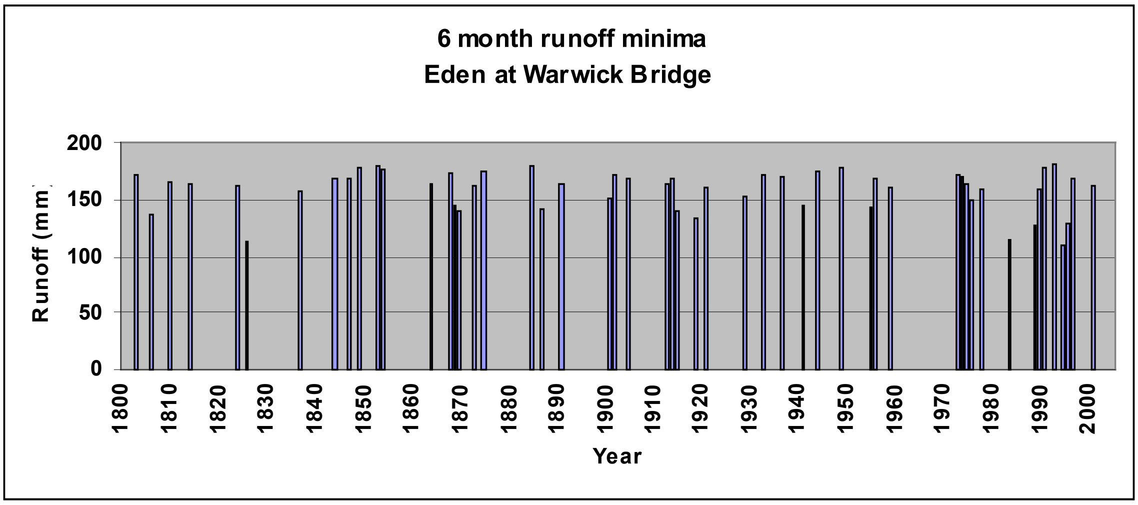
Figure 7: Maximum 18 month runoff minima for Ely Ouse at Denver Sluice (synthetic naturalised series 1801-2002).

Table 4: Minimum 6 and 12 month runoff totals for the River Eden at Warwick Bridge (synthetic naturalised series 1800-2002).

Rank	*6 month minima (mm)*	*% of long-term average*	*End month*	*End year*	*12 month minima (mm)*	*% of long-term average*	*End month*	*End year*
1	110.2	44.2	9	1995	466.3	56.5	6	1956
2	113.0	45.2	9	1826	475.2	57.6	6	1855
3	115.2	46.19	9	1984	476.7	57.8	6	1996
4	128.4	45.2	10	1989	481.2	58.4	11	1964
5	129.2	51.78	9	1996	488.4	59.1	3	1845
6	134.5	47.48	10	1919	490.7	59.5	9	1976
7	137.3	54.9	9	1806	495.1	59.9	12	1973
8	140.1	40.48	11	1915	496.1	60.1	3	1934
9	141.0	56.4	9	1870	505.2	61.2	2	1888
10	142.7	50.2	10	1887	506.0	61.4	10	1959
11	143.2	57.38	9	1955	506.4	61.4	5	1938
12	144.9	53.2	8	1869	523.2	63.4	8	1905
13	145.2	58.1	9	1941	524.4	63.6	8	1806
14	150.2	60.1	9	1976	526.3	63.9	11	1814
15	151.0	53.2	10	1901	531.7	64.4	2	1942

As columns 5 and 9 in *Table 4* confirm, there is limited correlation between the years that experience exceptional 6 month runoff deficiencies and those that register notable 12 month deficiencies. 1854-1855 does not feature in the minimum 6 month accumulations, but ranks highly in the 12 month category and forms part of a cluster of dry winters (see *Figure 8*). This would be a significant period for reservoir systems that are multi-year critical, notwithstanding the absence of exceptionally low runoff sequences through the summer half-year. A surprising absence from *Table 4* is the April-September 1990 period, which registered the lowest 6 month runoff total (for any start month) in the flow series for the Warwick Bridge gauging station.

It is evident from the above that final designations of the major drought episodes – for the Eden basin in particular – will be influenced significantly by the critical periods adopted for the later components in this study.



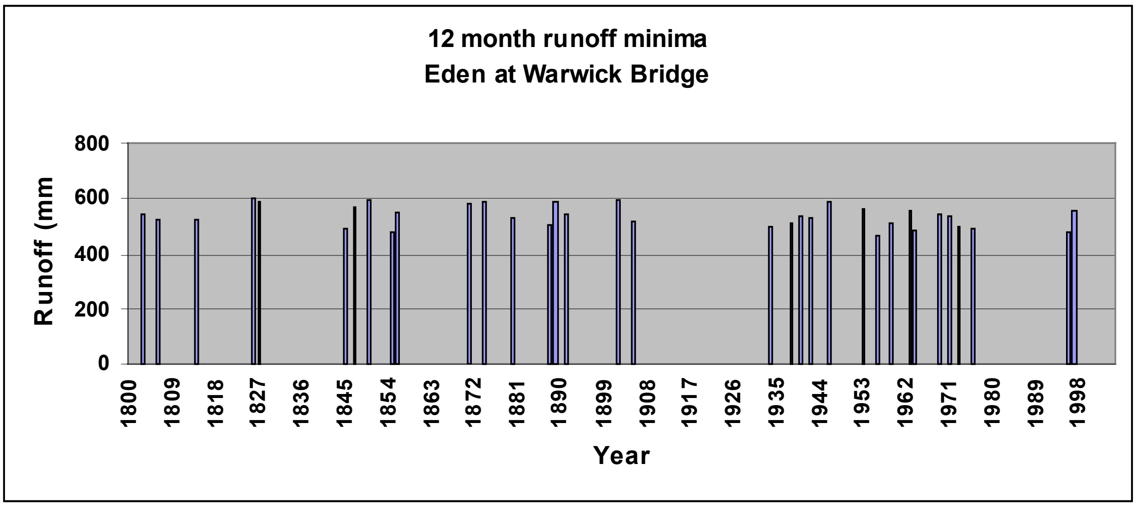


Figure 8: 6 and 12 month runoff minima for extended runoff series: Eden at Warwick Bridge (synthetic naturalised series).

4. Evidence of drought impact

A complementary study focused on collecting documentary evidence of the impact of the key drought episodes identified in Appendix 1 for England and Wales. The primary sources comprised:

i. The BHS Chronology of British Hydrological Events;
ii. Selected bibliographies of major British drought events (see references).

The BHS Chronology, launched in 1999 and available on the internet (http://www.dundee.ac.uk/geography/cbhe/), is an exceptionally valuable compilation of historical material, drawn from a wide range of sources (from the proceedings of the Institute of Civil Engineers to the *Gentleman's Magazine*). However, copyright restrictions mean the bulk of the contributions relate to the pre-1935 period. No detailed curatorial appraisal of the historical evidence was undertaken and, inevitably, the incomplete, local and anecdotal nature of much of the material implies that assessments of drought impact (and their spatial extent) are provisional. Evidence of impact for more recent events was gained from a thorough search of the academic literature, which contains many relevant or comparative reviews of droughts and is less anecdotal in nature than the BHS Chronology.

For some rainfall deficiencies identified in Appendix 1 (e.g., 1972-1973, 1962-1965, 1955-1956, 1949, 1943-1944, and 1937-1938, no impact evidence could be found. This could be for several reasons. Firstly, in some regions the moderating effect of groundwater may preclude the development of a hydrological drought from a meteorological drought, or the availability of local sources of supply (e.g., direct river abstraction and springs) may result in the impact being mitigated locally, such that it is not sufficiently unusual or severe to merit recording. Alternatively, the lack of evidence could simply reflect the lack of interest and/or personnel available for recording such hydrological events (e.g., the 1943-1944 drought took place during the Second World War). Conversely, the 1884 drought was noted in the BHS Chronology as being 'a remarkable year in the history of Fen drainage', with accounts of drainage engines being switched off to maintain supplies in the drains for cattle and fire fighting, yet flow and rainfall records from East Anglia suggested that it was a relatively moderate drought event.

Even with these known shortcomings, the documented evidence presented in Appendix 2 provides valuable support for the hydro-meteorological data (Appendix 1) and is important for gauging the changing vulnerability of England and Wales to drought through time. These appendices demonstrate clearly that the severe drought events of the 1970s, 1980s and 1990s are not unique within the context of the historical record. Indeed, the evidence suggests that the 1880s and 1890s suffered from a pronounced clustering of dry years (dry winters especially), with even more severe drought events than those during recent years. At that time the main impact of drought was borne by the individual; nowadays, the main impact is economic, with the individual rarely directly affected. For example, the drought and associated heatwave of 1995 resulted in £180 million losses for agriculture, £96 million for water supply and £380 million by the retail sector (Palutikof *et al.*, 1997). Similarly, the total economic cost of the 2003 drought to Europe was in excess of €11 billion (Munich Re, 2004). Major recent droughts, 1976 and

1995 especially, have helped change public and private attitudes to water supply and resource management and have acted as the catalyst for increased investment. For example, water transfers, the conjunctive use of groundwater and augmentation of local supplies through new or standby sources, introduced after 1976, helped to mitigate the impact of the 1984 drought, and ensured that supplies were maintained.

The Anglian and North West Regions are quite different hydrologically and are therefore vulnerable to different types of drought with varying impacts, as described below:

4.1 North West Region

Most water supply in the North West Region comes from surface water resources, which makes the region particularly susceptible to short duration droughts (1-2 seasons), particularly those that occur in the spring and summer when demand is at a peak. In the Eden area boreholes are critical to meet local rural water demands, although of low yield. The historical references provide many instances of public water supply failing or being severely restricted in the North West Region during the 19th and early 20th centuries. Comparison with Appendix 1, however, suggests that many of these impacts were associated with limited reservoir availability in particular localities, rather than all being associated with major droughts. During the ‘major drought’ of 1887 (driest calendar year in the region from 1868-1924) water supply to cities such as Manchester and Liverpool was restricted at night. In Clitheroe, failure of supplies resulted in water being imported into the town by rail in milk cans and distributed among the community by the stationmaster (one bucket per family). Similarly, in 1868 supplies to Manchester, Rochdale, Halifax, Sheffield and other major towns were restricted for increasingly longer periods of the day as the drought intensified during the summer. For instance, Rochdale residents had only 4 hours supply a day for a 15 week period from June 1868. There are also reports of water being sold by the bucket (half-a-penny in Hull and Beverley areas in 1884) and carted long distances for cattle watering. The Longdendale reservoirs (supplying Manchester) seem to have been particularly vulnerable to drought, and reached particularly critical conditions in November 1947 and 1929 ,respectively, with standpipes installed in 1947 (but subsequently not needed) for domestic supply.

The relative frequency of water supply problems at this time meant that the public probably accepted these restrictions as unavoidable. Industrial supplies, though restricted, also had precedence over domestic supply, with reports of mill-owners being compensated in money for any water deficiencies (e.g., 1929). This contrasts with the public resentment and publicity given to the introduction of standpipes in parts of Yorkshire and the north-west in the hot dry summer of 1995, as upland reservoirs, dependent on spring and summer runoff, could not cope with the unprecedented public demand for water. In response to this water shortage and the continuing drought conditions (into 1996 and 1997), Yorkshire Water Services announced, in April 1996, plans for a £50 million water transfer scheme from the Tees to the River Ouse to increase the resilience of the region against future droughts.

4.2 Anglian Region

The Anglian Region, with its dependence on groundwater (approximately 40 per cent of all licensed abstractions, constituting, for example, 73 per cent of the water supply in Cambridgeshire), is particularly vulnerable to long duration (multi-season) droughts when flows have been low for over 15 months and winter groundwater recharge has been minimal. In groundwater-fed catchments exceptionally hot dry summers, such as in 2003, can be accommodated provided there has been adequate winter recharge.

In this region, evidence for drought focuses on reports of failed springs, shrinking stream networks, failed or low groundwater levels in wells, dried up ponds, agricultural crop damage and reduced yields, and (in earlier times) carting of water for cattle watering. Specific reports of failure of public water supply include restricted supply in Northampton in 1884 (short supply for 1 year), Ingoldsby, Lincolnshire, in 1911 (when water was shared out to parishioners twice a day) and water being sold for 6 pence a bucket in Sussex in 1899. Notable droughts in terms of impact include 1995-1997, 1990-1992, 1976, 1933/19334 (mainly Essex), 1911, 1890-1909 (especially 1890, 1901-1902, 1904-1906), 1874-1875, 1869 and 1851-1852.

Overall, there are surprisingly few references to poor water quality, the only one being to the River Waveney at Diss, Norfolk, reported as being 'nearly stagnant, and the water black, filthy and polluted' in July 1874. This is supported by evidence from across the country, such as a typhoid outbreak in Mountain Ash, South Wales, in August 1874, and the River Exe at Exeter in 1874 being described as 'little better than a sewer'. Although there are no specific reports in this area, cholera outbreaks in the 1840s were not uncommon, given the lack of running water supplies, cesspits and well contamination common in cities at that time. In 1848-1849, 6000 fatalities were reported for a cholera outbreak in south London and in 1858 'The Great Stink', from the backed up Thames, caused thousands to flee the City.

5. Evidence for drought pre-1800

The evidence for drought (pre-1800) is even more patchy and anecdotal than that from the later period, with few comments providing any indication of the relative severity of each event. Documentary evidence was taken from two main sources, as outlined below:

i. The BHS Chronology of British Hydrological Events;
ii. *River-flow data for the United Kingdom: Reconstructed data back to 1844 and historical data back to 1556* (Jones *et al*., 1984).

In Jones *et al*. (1984) there are many references to drought in the Ely Ouse area from 1563 onward, with comparatively fewer references for the Eden catchment in the north-west. Without a more detailed literature search it is impossible to substantiate whether this is a true reflection of drought incidence or just the emphasis given to reporting such events. Writers of certain eras may have expressed themselves more boldly than would occur today, with the term ‘drought’ often used loosely to describe a short dry spell.

The very sparse raingauge network in the 18th century, with little or no upland coverage, implies a necessary caution in interpreting contemporary drought reports. It is clear, however, that in the 1700s, as in the 1800s, the UK suffered from clusters of dry seasons or dry years (e.g., dry springs and summers during 1740-1744, 1780-1781, 1784-1786, 1788-1789) that would have particularly placed the groundwater fed resources of East Anglia under stress. Other notable dry periods in the south included 1590-1592 (‘Thames in parts nearly dry)’ 1634-1637 (cluster of dry springs and summers), 1666-1667 –(most intense in July 1667, with ‘no travelling in the road or streets in London for dust’), 1684-1685 –(reports of dried up ponds, rivers and springs) and clustering of dry years in 1689-1692 and again in 1694-1695. Shorter two-season spring and summer droughts accompanied by high temperatures occurred in 1699 (‘ground dry by May’), 1705 (‘such a dry season has not been known for many years’), 1736, 1765 and 1788. In the Eden catchment, hot dry summers are noted in 1682, 1705, 1714, 1719, 1723, 1731, 1741-1742 and 1743, and if shortage of water in the Trent and Mersey Canal can be taken as a measure of drought ‘the years 1785, 1788-1789, and 1791 were particularly bad, although even in a good year many boats had to navigate with half loads in the dry season’.

There is evidence from different sources of widespread drought conditions in 1740, 1741 and again in 1743. The north (Wharfe catchment) seems to have been affected in 1740 (April–June) and again in October 1743, as were groundwater-fed catchments in East Anglia and southern England in 1741. For example, in 1741 the drought was reported as being ‘very severe at Pode Hole’, with reports from the Ely Ouse that ‘the spring and summer were so dry that from January to August there was scarce half the rain which normally falls in that time’. Similarly, in Atcham, Salop dry weather was referred to between 21 March and 10 May 1741. In July 1741 in Willenhall, ‘The ground perhaps was never more dry than now, the springs low, pits dry, and great scarcity of water hereabouts’, while in Cheltenham Spa, Skillicorne writing of his progress states that ‘... The summer 1741 proving very dry, 30 trees dead ...’ ‘[133 limes and elms had been planted on upper and lower walks over the winters of 1738-1739 and 1739-1740]’. 1743 was noted as a particularly dry year in the BHS Chronology, supported by the comment that ‘the greatest part of this summer was so dry a one, that many people took as much care of their pond-water, as some do of their beer’.

In 1780-1781, an extended dry period led to groundwater problems, with reports of springs failing in Derbyshire Derwent during the long dry summer of 1780, and wells failing and ponds dry around Selborne, East Hampshire, in September 1781.

1784-1786 was another extended dry spell (the lowest 6, 12 and 24 month rainfalls for England and Wales), which reached its maximum intensity in the summer heatwave of 1785, with impacts felt across the country. As Gilbert White (Selborne, Hants) reported, ‘Severe drying exhausting drought. The country all dust’. Thomsen (1993) quotes an extract from a millowner’s journal in Norwich in which he reports that ‘there was no water at the mill from June 23 to July 1 1785, therefore unable to make or sell any flour’. Drought also affected other industries that were dependent on running water for power and processing (flour milling, textiles, dying). During this year, major heath and forest fires were reported from as far apart as Rothburg Forest, near Newcastle-upon-Tyne, to Easthampstead, Berkshire. The Rothburg Forest fire led more than a thousand acres of sheep ground and heath being rendered totally useless.

1788 was another dry year across the country, with the lowest 3 month (October–December) rainfall in Kew from 1697-1970. Reports from the River Irk (Mersey and Irwell) in June 1788, ‘From the beginning of April to the later end of June 1788 was a severe drought attended with uncommon heat’ and from the Bristol area ‘This year saw the commencement of a series of bad harvests ... due to a severe drought’ provide supporting evidence for this.

6. Conclusions

This study has successfully identified key drought events in England and Wales since ,1800 based on a range of hydro-meteorological evidence, and provided documentary evidence of the impacts for each event. The report also examined the rather patchy documentary evidence for drought pre-1800 and found clusters of dry years in 1740-1743 and especially from 1780 to 1790. In the time available, it was not possible to examine seemingly contradictory documentary evidence relating to drought magnitude or extent, or to reconcile discrepancies between assessments of drought severity derived from climatological and those from hydrological data. Nonetheless, the major droughts identified are generally in good agreement with those identified by other authors using different indexing criteria. In addition, the material presented in the appendices is believed to be more comprehensive than that presented in earlier drought studies for England and Wales.

It is clear that throughout the historical record, drought has been a recurring feature of the UK climate, with recent drought events by no means exceptional in terms of their intensity or duration. The impression from this limited study is that there is a repeated tendency throughout the historical record for dry years to cluster together, which results in multi-year droughts that contain shorter, more intense periods (e.g., 1798-1808, 1854-1860, 1890-1909, 1990-1992 and 1995-1997). The more protracted clusters predate most observed river-flow and groundwater time series. As a consequence there is a clear danger that contemporary data sets (post-1950) may be unrepresentative of the full historical series, and thus drought risk (particularly in relation to protracted events) is being underestimated. However, recent advances in drought mitigation, planning and infrastructure have meant that many regions of the UK are now better able to cope with extended rainfall deficiencies than in the past. The impression based on England and Wales rainfall series is that there does not seem to be any increase in frequency of shorter duration (12 month) dry episodes, although summer half-years appear to be becoming more arid, largely through increased temperatures. These impressions clearly need to be investigated further in a more rigorous analysis of UK rainfall and runoff deficiencies.

The study has highlighted some difficulties of examining drought and its impact in an historical context. The first relates to possible changes in climatic variability over the historical record, in particular to the partitioning of rainfall between the winter and summer half-years – this merits further investigation. Secondly, a region’s vulnerability to drought is constantly changing depending on the supply infrastructure, the surface–groundwater balance and the demands placed on the water supply system by users. In the 19th century drought directly affected peoples’ livelihood and water supplies, but these days the impact is mainly economic, with cuts in water supply rare. Indeed, the public outcry over water shortages in 1995 in the north-west and Yorkshire led to rapid improvements in infrastructure and flexibility of supply. Increasingly flexible, multi-source supplies imply that the critical period for drought in most catchments is being extended. Lastly, documentary evidence of drought is patchy and tends to decline the further back in the historical record one goes, which gives a false impression of drought incidence.

At a catchment level, drought vulnerability is even more dependent on the surface–groundwater balance and water resource management structure. It cannot be assumed that major national droughts will always impact at catchment level, because of the high spatial variability in drought intensity and that the most intense part of the drought may not coincide with the critical period for catchment water resource provision. A preliminary identification of key historical droughts in the Eden and Ely Ouse catchments is presented based on 6 and 12 month runoff deficiencies (Eden) and maximum 18 month runoff deficiencies (Ely Ouse). A final selection will depend on the identification of the most appropriate critical period for water resource provision in these two catchments.

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Appendix 1: Drought episodes in England and Wales – a preliminary appraisal

References to impacts in this table refer primarily to river flows (SW) and groundwater levels (GW). The most severe events are shaded.

Year	*Duration*	*Focus*	*Comments*	*East Anglia*	*North West England*
2003	Two season Late winter to autumn	UK coverage	Episodic, wet late spring to early summer, then intense drought with exceptional high temperature well into the autumn. Most intense in south-east. Very healthy GW levels in January, hence limited GW dimension.	Moderate – limited GW impact	Substantial rainfall deficiency – principally SW impact
1995-1997	Spring 1995to summer 1997	As above	**Major drought**. Third lowest 18-month rainfall total for England and Wales (E&W) (1800-2002). Long duration drought with intense episodes (e.g., affecting eastern Britain in hot summer of 95). Initial surface water stress, thence very depressed groundwater levels.	Major drought; SW and GW impacts	Major impacts on SW and GW
1990-1992	Spring 1990 to summer 1992	Most regions of UK	**Major drought**. Similar focus to 1988–1989 drought – reflected in exceptionally low GW levels (in summer 1992, overall GW resources for E&W probably at their lowest for at least 90 years). Intense phase in the summer of 1990 in southern and eastern England.	Major impact on SW in 1990; thence major impact on GW	Moderate
1988-1989	Autumn 1988to early winter 1989	Southern and north-east Britain	Winter drought heralded large rainfall deficiencies by late autumn. Significant groundwater impact in 1989. Dramatically terminated over winter of 1989–1990, but reinitiated in the spring (see above).	Moderate – 1989 summer rainfall around average	Moderate–very low flows in summer–autumn 1989
1984	Late winter–to autumn	West and north Britain	Notable drought. Intense two-season surface water drought. Designated drought in parts of northern Britain, but bracketed by wet periods. Little groundwater impact.	Modest impact	Major drought – very low April–August runoff
1976	May 1975to August 1976	All regions of UK (Scotland?)	**Major drought**. Lowest 16-month rainfall in E&W series (from 1766). Extreme in summer 1976. Benchmark drought across much of E&W – particularly the English Lowlands. Severe SW and GW impacts.	Major SW impact and very substantial GW impacts. Extremely hot summer.	Major drought (primarily SW impact, and less severe drought than in English Lowlands)

1972-1973	Summer 1972 to late 1973	Most regions affected	Sub-critical event in most areas (summer rainfall in 1973 was near average), but major impact on the Chalk – (and possibly the Permo-Triassic of the north-west); flows in spring-fed rivers very depressed.	Notable GW drought – substantial impact on flows in rivers draining impermeable catchments	Very notable runoff deficiency (lowest annual runoff for the Eden) – but summer flows not extreme
1962-1965	Autumn 1962 to summer 1965	Most regions	Sequence of dry winters. The west affected in 1963–1964 (lowest flows in autumn of 1964), but greatest impact on river flows in the south; lowest February flows on record in Sussex and Hants in 1965.	Moderate (but with considerable SW and GW impact in 1965)	Moderate
1959	February to November	Most of E&W affected	**Major drought**. Intense 2-3 season drought – most severe in eastern, central and north-eastern England. Significant spatial variation in intensity. Modest GW impact.	Severe February–September rainfall deficiency (in the east especially). Very depressed flows but very limited GW impact	Substantial SW impact – autumn flows especially
1955-1956	Summer 1955 to summer 1956 (lingered in some regions)	Western and northern Britain	Severe in parts of western and northern Britain (including north-west England). But wetness of the summer in 1956 moderated impacts. (Designated drought in eastern Scotland.)	Modest – low flows during 1955–1956 winter	Notable drought
1947-1949	Summer–autumn (rainfall deficiency stretches back to 1947)	English Lowlands	Sharp late summer–autumn drought in 1947 (featuring a long hot summer). Thence sustained limited recharge produced depressed groundwater levels for lengthy periods (but above recent minima) in English Lowlands. Intense phase in summer of 1949 – wider impact.	Significant SW impact in 1947. Later significant GW impact following successive dry winters	Considerable SW impact in summer of 1949, otherwise moderate
1943-1944	Spring 1943 to autumn 1944	Southern Britain	Eighth ranked 18-month rainfall deficiency for E&W. Moderately severe in parts of Anglian Region and Yorkshire. Impacting principally on high baseflow lowland rivers (reflecting substantial GW impact because of longer term rainfall deficiency).	Notable SW impact, locally 'major' (lowest October–March runoff for the Ouse). Significant GW impact	Modest
1941	Summer	Northern England	1941 – moderate event, but very low summer river flows in north-west.	Only significant in 1943	Substantial SW impact in 1941
1937-1938	Summer 37 to autumn 38	Wales and the south	Primarily a SW and eastern England drought (when summer rainfall in 1938 had little hydrological effect). Notable on the River Wensum, and depressed winter runoff in the north-west.	Moderate	Depressed winter flows but moderate overall

1933-1934	Late autumn 1933 to autumn 1934 (shorter in north-west)	All regions	**Major drought**. Intense across southern Britain. Severe SW impacts in 1933 followed by severe GW impacts in 1934, when southern England heavily stressed (less severe in the more northerly, less responsive, Chalk outcrops).	Major SW impacts. Lowest 18-month runoff on the Ouse (Thames also)	Locally 'major' in parts of north-west (especially in 1934 where supply source is North Wales). Severe winter runoff deficiency – but above average summer rainfall moderated impact in many areas
1929	Late 1928 to September 1929	Most regions	Severe surface water drought; very widespread impact (including North West and Anglian Regions). Large runoff deficiencies until autumn, then rapid recovery. Little groundwater impact. Dramatic termination.	Notable SW drought; appreciable minor GW dimension	Modest
1921-1922	Autumn 1920 to early 1922	Most regions	**Major drought.** Second lowest 6-month and third lowest 12-month rainfall totals for E&W. Very severe across much of E&W (including Anglia and south-east; parts of Kent reported <50% rainfall for the year); episodic in north-west.	Major SW impacts in latter half of 1921 (heralding low GW levels in 1922)	Notable three-season drought in 1921
1919	Early spring to early winter	Northern England	SW drought (but following wet winter).	Moderate – but notable May–November runoff deficiency on the Eden	Not major, similar to 1921
1914-1915	Spring–autumn	Northern England	Notable in north-west – Eden significantly affected. Otherwise limited impact.	Not significant	Major two-season drought. Driest May–October on record
1913	Spring–autumn	North and west	As above. Moderate event (but very dry summer).	Not significant	Moderate but very dry late summer and autumn
1911	Spring–autumn	Southern Britain	Moderate event hydrologically but extremely hot summer. Not significant in north-west. More notable in eastern England. Lowest flow on record for synthetic Thames (Eynsham) series – but not supported by Teddington flows.	Moderate SW impact. Very hot summer. GW levels low but above drought minima	Not significant
1890-1909	Long drought (see next six entries)	Southern Britain?	**Major drought – long duration** (with some very wet interludes). Exceptional cluster of relatively dry winters. Major and sustained GW impact. Most severe phases: 1893, 1899, 1902, 1905. Merits separate investigation.	Major and sustained SW and GW impacts (but damp summers moderated water supply and agricultural stress)	Far less notable than in English Lowlands (north-west less susceptible to protracted droughts)
1908-1909	Summer 1908 to summer 1909	English Lowlands?	Exceptionally dry late winter to spring in eastern England, heralding very depressed groundwater levels in parts of the eastern Chalk.	Very depressed GW levels	Not significant
1904-1906	Spring 94 to autumn 1906	All regions	Modest impact in north-west. 1904-1905 winter very dry in southern Britain (where drought lingered into 1906).	Very depressed river flows and major GW dimension	Substantial – very depressed spring–autumn runoff

1901-1902	Late winter 1901 to late autumn 1902	Large spatial variations	Major drought episode. Severe in north-west, south-east and Anglia (depressed GW levels in 1902). Major impact on spring flows and Chalk streams.	Major drought. As above. (1902 second lowest annual runoff for Thames; flows depressed on Great Ouse also)	Sustained rainfall deficiency including two dry winter–spring periods
1898	Autumn 1897 to winter 1898	Southern Britain	No drought in the north-west. Largest impact in English Lowlands where dry winter of 1898-1899 ensured continuation of drought in limited parts of south and east (very low GW levels in 1898).	Very depressed river flows and GW levels	Not significant
1893-1896	Varies with region	Midlands and south	Initiated by very severe rainfall deficiency in spring 1893, thence arid summer. Re-intensified in spring 1895. Southern and northern Chalk outcrops only moderately affected. Therfield depressed – suggests south-east? focus	Substantial (possibly major) drought 1892-1893 winter half-year exceptionally dry – and intense in summer 1893 (73-day absolute drought in East London)	Modest SW impacts
1890-1891	Late 1889 to summer 1891	North and south?	Significant impact in Anglian and North West Regions.	Moderate–low GW levels in 1891	Moderate
1887-1888	Late winter 1887 to summer 1888	West and north	**Major drought.** High ranking rainfall deficiencies across a range of timeframes. Very widespread (across most of British Isles). Extremely dry 5-month sequence in 1887. Primarily a SW drought – severe in western Britain (including north-west).	Moderate, with modest GW impacts	Major drought – sequence of three dry winters. Most severe in summer 1887. Derwentwater fell to lowest level on record
1884-1885	Early 1884 to late 1885 (spatially variable)	Northern and southern England	Impact (but not severe) in North West and Anglian Regions.	Moderate	Modest
1873-1875	Late 1873 to early 1875	English Lowlands	Notable (but not outstanding) rainfall deficiencies across a range of timeframes. Very significant (possibly major) in east (e.g., Wensum) and south. Exceptionally dry winter followed by dry summer. Barely significant in north-west.	Possibly Major drought. November–April drier than 1975-1976. Severe SW impacts	Not significant
1869-1871	Spring 1869 to summer 1871	All regions	Exceptional 6-10 month rainfall deficiencies. Notable three-season drought following a wet winter. Most severe in the north. Limited GW impact in southern Chalk (but Wendover – moderate impact). Very arid summer half-year. Very low summer flows in north and English Lowlands.	Notable SW impacts	Possibly major – 1869 and 1870 both feature notably low 6-month runoff for the Eden
1867-1868	Autumn 1867 to late 1868	All regions?	Notable drought in spring–summer of 1868 – very hot summer.	Moderate	Moderate

1863-1865	Late 1863 to autumn 1865	Western Britain		Moderate – but notable on the Ouse?	Moderate
1854-1860	Long drought (see next two entries)		**Major long duration drought**. Sequence of dry winters in both the English Lowlands (seven in succession at Oxford) and northern England. Major and sustained GW impact.	Major drought. Cluster (six out of seven) dry November–April periods. But damp summers moderated community impact	Major drought. Notable cluster of dry winters. Substantial SW and GW impacts (moderated by normal summer rainfall)
1858-1859	Autumn 1857 to early 1859	National	Notable drought. Extremely dry November–March 1857-1858. Widespread impact – severe GW impact at Chilgrove.	Moderate	Culmination of sequence of five dry winters
1854-1855	Autumn 1853 to late 1855	National	**Major drought**. Second lowest rainfall across wide range of durations for E&W. Widespread impact. Severe in north-west and Anglia; very major impact at Chilgrove. Successive very dry winter periods.	Major drought (some relief in wet July 1855)	Major two-season drought, following successive dry winters
1844-1845	Spring 1844 to spring 1845		Very low 12 and 18 month rainfall totals for E&W. Notable long drought in north-west – and significant GW impact at Chilgrove (but summer half-years not especially dry).	Needs further investigation	Very dry winter, but summer rainfall not exceptional
1826-1827	Spring 1826 to autumn 1827	National	Very notable two-season drought in southern Britain? Exceptionally dry March–July, in north-west particularly. Significant GW impact following two dry winters.	Extremely hot summer but modest SW & GW impact	Major drought (on limited evidence); second lowest 6-month runoff for the Eden
1814-1815	Winter–summer	Northern England?	Most severe phase of longer term (1813-1816) rainfall deficiency.	Fifth ranking 18-month runoff deficiency on the Ouse – possibly major	Notable winter–summer drought
1798-1808	Long drought (see next two entries)		**Major long duration drought.** Three separate (non-overlapping) periods feature among the dozen lowest 18-month rainfall totals for E&W. Limited direct hydrological evidence. Further investigation needed.		
1806-1807	… spring 1806 to autumn 1807 …	?	About fifth lowest 24-month rainfall for E&W (1800-2002)	Moderate	Severe?
1802-1803	January 1802 to late 1803	National	Very dry 12 months to October for E&W (fourth lowest 12-month accumulation). Temporally distribution of rainfall limited its hydrological effectiveness – hence likely severe GW impact, especially in English Lowlands.	Major?	Not significant

Appendix 2: Documentary evidence of drought impacts in England and Wales (1800-2004)

Date	Duration	Focus	Evidence of drought impact across England and Wales (primary source BHS Chronology, other references quoted)
2003	Two season Late winter to autumn	UK coverage	• Impact on UK water supply system modest compared with the rest of Europe, due to mitigation strategies and excellent status of UK water resources early in 2003.[2] . No hosepipe bans or restrictions on essential water were required;[2] some requests to moderate non essential demand (reduced garden sprinkling); spray irrigation restrictions widely applied.[2]. One drought order[1] (North West Region). GW moderated drought impact in south-east, though with wide regional variations. Compton well (Chalk) water levels briefly reached minimum level since 1893. Village ponds dried up[2]. • Dry autumn soils gave problems in raising beet crops in Midlands and autumn sown crops (e.g., oilseed rape failed to establish).[2] • Stress on fish and other aquatic fauna associated with high temperatures and low flows. • General water quality deterioration caused by low dilution/blue–green algae.[2] • Associated heatwave resulted in 2045 deaths, especially among the elderly.[3]
1995-97	Spring 95 – Summer 97 Heatwave late June-August 1995	UK coverage	• Summer 1995 severe pressure on surface water resources and distribution systems (additional costs approximately £96 million), especially in Regions dependent on spring and summer runoff (e.g., South West, Yorkshire, North West and Midlands). Supply unable to cope with unprecedented peak demands, particularly for garden watering.[7] Increased GW and river abstractions made to maintain supply. Publicity campaigns launched by water companies (e.g., Staffordshire Water Company). • Water supplies restricted through statutory measures: **1995:** 53 drought orders[1] imposed in E&W (23 North West; 21 North East; 1 Midlands; 1 Southern; 7 South West); 18 million people affected by hosepipe bans (especially in NW, SW and Yorkshire);[5] garden watering bans in localised areas of southern England;[6] applications made for rota cuts and standpipes in West Yorkshire, causing considerable consumer resentment and publicity;[5] late 1995 water shipped from Northumbria to Yorkshire to maintain supplies, with temporary pipeline between the Tees and Swale to alleviate local shortages.[7] **1996:** 44 drought orders[1] in E&W (12 North West; 18 North East; 2 Midlands; 5 Southern; 5 South West) includes 1 order in North West for environmental purposes. **1997:** Three drought orders[1] in E&W (1 Anglian; 2 Southern). Severn-Trent imposed a region-wide hosepipe ban at the end of August 95, which was not lifted until mid-January 1996 in most areas; abstractions for spray irrigation restricted.

			In Anglian Region:[4] Improvements in communicating water conservation to the public since 1988-1992 drought and increased number of metered customers on measured supplies, provided successful management of demand and no restrictions were introduced. As a precautionary measure against the continuation of drought into the third year Drought Orders were applied for in September 1997 to assist winter refill of Grafham and Pitsford reservoirs – these were subsequently withdrawn following above average rainfall. • 20,000 fish died in River Trent, but many saved due to pumping of liquid oxygen into Trent by National Rivers Authority (Midlands, Environment Agency). During 1997 Southwest Water began releasing reservoir water into the Exe and Tamar to try and save salmon and trout fisheries (Phillips and McGregor, 1998).[20] • Agricultural losses[6] of £180 million, particularly to livestock farming, reduced yield for root crops, and vegetables. • Losses[6] also by water supply and buildings insurance sectors (£326 million for subsidence-related claims). Large losses in retail sector, especially for clothing. • Deciduous tree condition in south England adversely affected. • Some positive impacts[6] from the hot dry summer in 1995 were health and reduced energy consumption and increased yield of some arable crops.
1990-1992	Spring 1990 to summer 1992	Most regions of UK	• Biggest impact on water supply in areas with greatest pressures on resources, especially in areas of high irrigation demand.[1] Statutory restrictions on water supply imposed. **1990**: 61 drought orders[1] (17 North East; 3 Anglian; 2 Thames; 25 Southern; 13 South West), 19 million people affected by hosepipe bans;[5] abstractions for spray irrigation banned in some Fenland catchments in late July 1990.[8] **1991**: 28 drought orders[1] (1 North West; 9 North East; 18 Southern), 6.5 million people affected by hosepipe bans.[5] **1992:** 16 drought orders[1] (1 North East; 3 Thames; 11 Southern; 1 South West); 6.75 million people affected by hosepipe bans.[5] • Severity worst in east and south where resources based on GW or GW-fed rivers[9] (e.g., River Wensum at Costessy Mill – greatest cumulative runoff deficit since at least 1850, followed by 1948-1950, 1972-1974), deficit lasted over 3.5 years; Chilgrove well, Sussex – below average since mid-1988, but other more prolonged and extreme falls in the record; Dalton Home borehole (Chalk) of Yorkshire below average since mid-1988, which is without precedent and lower than 1904-1907. Although peak intensity less than 1975-1976, accumulated deficits were largest for at least 50 years. • Spring-fed rivers contracted.[9] Worst shrinkage in stream networks since before 1976. Migration of river head downstream in lowland spring-fed rivers and even in low abstraction catchments in Yorkshire Wolds.[8] Less unusual in other parts of south England but still extreme. From late 1990 lengthy stretches of dried up river bed reported,

			exacerbated by rising abstraction rates. Considerable loss of amenity and aquatic environment.
1988-1989	Autumn 1988 to early winter 1989	Southern and north-east Britain	• River flows consistently below mean for more than 3 years (1988-1992). • 1989: 89 drought orders[1] (21 North West; 9 North East; 5 Midlands; 1 Anglian; 19 Southern; 21 South West); 6.5 million people affected by hosepipe bans;[7] water transferred to Wear Catchment via Kielder tunnel obviated water restrictions in Durham and Sunderland.
1984	Late winter to autumn (most intense in August)	West and north Britain	• Drought impacts less severe than in 1976 with only minor impact on agriculture.[8] • Shrinking river networks, failure of springs, dry rivers reported in Dartmoor, Cumbria (River Kent). Rapid decline in river levels and reservoir stocks. Water transfers between catchments, conjunctive use of groundwater resources (set up following 1976) and augmentation of local supplies through new or standby sources helped mitigate the impact and ensure that supplies were maintained. 104 drought orders in England and Wales[1] (31 North West; 6 Midlands; 45 South West; 22 Welsh, including 3 jointly with Midlands), mainly to reduce compensation flows and river abstractions;[8] 23 million people affected by hosepipe bans throughout the west and north of England and Wales, but although contingency powers to restrict demand were requested no standpipes or rota cuts were necessary;[8] new absolute minimum flows for hydroelectric power HEP schemes set in July–August.
1976	May 75 to Aug 1976	All regions of UK	• Drought had major impact on private and public attitudes to water supply and resource management. • Major water supply problems for both surface- and groundwater-fed catchments. Minister of Drought appointed and the Drought Act (1976) was rushed through Parliament on 6 August 1976. Peak of drought coincided with holiday season giving particular problems to south-west England. Many people in south-east Wales, north Devon and Cornwall had water rationing. Routine rota cuts of up to 17 hours a day affected 1 million people in south-east Wales from between seven and eleven weeks from July to September 1976 and 2200 standpipes erected in north Devon in September 1976 to serve 160,000 people.[12] Water rationing in Jersey.[13] Massive save-water campaign and increased recycling of water in production processes. 136 drought orders[1] (18 North East; 13 Midlands; 15 Anglian; 8 Thames; 4 Southern; 58 South West; 20 Welsh); 48 million people affected by hosepipe bans.[5] • Flexibility in supplies was crucial for determining regional impact of drought (e.g., water shortages in Northampton avoided by transferring supplies between reservoirs; also in Yorkshire all reservoirs were drawn down equally).[12] • Drought and heatwave combined to produce many heath and forest fires, especially in Wales and southern England. • Thousands of subsidence claims, especially in clay areas (total cost £60 million, 20,000 claims).[12] • Agriculture suffered badly, with more than £500 million in failed crops. Cereal yields 10-15 per cent below 1970-1974

			average and potato yields 25 per cent below,[12] especially in North Midlands. Fodder yields significantly reduced in Wales and the south-west[12] and winter fodder used to feed livestock as grazing meadows were scorched.[14] Reduced milk yields and higher feed costs and import of cereals and vegetables resulted.[12] • Drought did not have significant detrimental impact on industry on a national scale, largely through implementation of water savings and priority given to maintaining industrial supply rather than domestic supplies.[12]
19721973	Summer 1972 to late 1973	Most regions affected	Some environmental impacts but no evidence of impact found.
1962-1965	Autumn 1962 to summer 1965	Most regions	Example of meteorological drought in which groundwater reserves moderated impact so that a hydrological drought did not develop, as no evidence of impact found.
1959	February–November	Most regions affected	• Low reservoir inflows (e.g. Minningsby Beck, inflows to Revesby Reservoir, Leicestershire) – longest dry spell (July to November) of effectively zero runoff between 1927 and 1970. • Statutory restrictions on supply with 51 drought orders and 10 million people affected by hosepipe bans.[5]
1955-1956	Summer 1955 to summer 1956 (lingered in some regions)	Western and northern Britain	No evidence of impact found.
1947-1949	Summer–autumn (rainfall deficiency stretches back to 1947)	English Lowlands	Some localised problems, e.g.: • [16]Water supply problems experienced at Longdendale reservoirs (supplying Manchester) in the north-west. 'Rainfall at Longendale from June to October 1947 inclusive was 9.44 inches, the lowest ever recorded for those 5 months since … 1855 … The combination of rainfall deficiency and excessive overdrawing quickly depleted reservoir stocks and an acute water shortage developed.' Agreement was reached with River Etherow millowners for a reduction in weekly compensation water discharged into the river and urgent and sustained appeals were made for voluntary reductions in consumption, but with no appreciable success. By 1 November only 16 days supply was left and arrangements were made to curtail domestic (but not industrial) supply by cutting off mains services and installing 710 standpipes, located

			so that no consumer would have to carry water more than 400 yards. 200 service personnel and water carts were deployed to supply water to the elderly and infirm and leaflets were distributed to all householders. Heavy rain on 10 November (10 days supply left), but the following days resulted in these emergency measures not being required. A drought order (13 November) and the 1950 Manchester Corporation Act provided for reductions in compensation flows and standpipes in subsequent droughts.
1943-1944	Spring 1943 to autumn 1944	Southern Britain	No evidence of impact found.
1941-1944	Summer	Northern England	No evidence of impact found, although recognised as a drought by the Environment Agency in the East Midlands region.
1937-1938	Summer 1937 to autumn 1938	Wales and the south	No evidence of impact found.
1933-1934	Late autumn 1933 to autumn 1934 (shorter in NW)	All regions	• Serious water shortage in many districts, especially in rural areas of Essex. • Low GW levels: First time no water in Kew well since 1914; lowest average annual water level at Compton, West Sussex (chalk well) for 50 years (1893-1942); in Warminster, 'For weeks the village had only two sources of supply: 2 wells. When these dried out, the villagers were reduced to catching every possible drop of rainwater in a desperate attempt to carry them through ...' (*Warminster Gazette*, 1934). • Low reservoir inflows and reservoir levels uncovering bridge in October 1933 seen on only 1-2 occasions since first fill in 1914 (Derbyshire Derwent headwaters). • Many woodland fires during August and September, including Derwent valley, near Matlock. • January 1934 – upper turf moor rhymes (River Cary, Somerset) perfectly dry yet usually full to overflowing. Their present dryness appears to be a record.
1929	Late 1928 to September 1929	Most regions	Few references to drought impact in BHS chronology • Anglia and south east: Thorney Drainage Board, Lincolnshire, records great shortage of water; too low in Thorney River for syphon to work; recession of head of Ems lavant; Kew Observatory – float rested on bottom of well for 13 days; water level in chalk well in Kent low reaching maximum depth below surface on 15 March 1930.

			• North west: Woodhead Reservoir of Manchester Corporation Waterworks, at the head of the series of Longdendale valley reservoirs, 'In July 1929, that reservoir was practically empty, while by the end of November the water was only 7 feet below top water level'; Huddersfield reservoir supplies, 'The drought of 1929, though not so severe [as that of 1934], involved the Corporation in a claim by the Meltham Mill Owners Association for £82 2s 4d'.
1921-1922	Autumn 1920 to early 1922	Most regions, especially the south	Major drought across whole of the UK, especially in southern England. Driest year in the south of England since 1788; driest year at Kew from 1697 to 1970; two stations in London recorded no rain for 72 days (March-May 1921). Relatively few reports of impact: • Dry rivers and recession down valley of streams (e.g., River Ems in Sussex, River Kennet in Wiltshire 16 miles shorter by December 1921, River Mole dry from Box Hill to Leatherhead). • At Timsbury near Romsey (Sussex) no GW recharge from February 1921; at other sites negligible percolation into GW; springs failed to provide adequate supply for mid Glamorgan. • Stratford had to rely on one well for town water.
1919	Early spring to early winter	Most regions	• 'The most conspicuous and, indeed, the only widespread period of drought in 1919 occurred in May and June ... At four stations, Tenterden, Brighton, Eye (near Peterborough) and Bradwell-on-Sea the period [of partial drought with mean rainfall not exceeding .01 in. per day] reached 50 days, in each case from 1st May to 19th June.' • 'In 1919, a very dry summer, West Sedgemoor hay was selling at £12.10.0 a ton.'
1915	Spring–autumn	Northern England	• November – localised dry areas in the western Pennines and Lake District with threat of water shortage to neighbourhoods where such an event is regarded as the remotest contingency. 'The districts most severely affected ... during ... the four months, August to November ... had a total less than half the average amount ….'
1913	Spring–autumn	North and west	Kendal district rainfall equalled only in 1870 during previous 108 years; maximum number of days in August with no rain since 1880: • Dry springs, ponds and ditches observed in November–December in Northumberland and Yorkshire; low springs observed in Devon, Lake District and Northumberland (Coquet) in October–November. Rivers in Snowdonia dry in places; bogs drained dry. Ullswater at lowest for 50 years (mark cut in rock). • Water shortages (e.g., in Neath , Cerrig y Digion, North Wales, Bolton-by-Bowland, Yorkshire (failed completely) or

			consumers put on half rations). • Butter famine in Midlands. • Land too hard to be ploughed (Severn). • In Lake District (August) parts of mill shut down for lack of water.
1911	Spring–autumn Very hot and dry July–September. Evaporation rates higher than in 1933 or 1921 (Camden Square, London)	Mainly Southern Britain	• Dried up wells and ponds reported in Hampshire, Nene catchment, Evesham area, Herefordshire, Calder and Derwent. In Trent–Derwent area, 33 ft deep wells dried up (August 19) as did many ponds that had never, in the recollection of the oldest inhabitant, been dried up before. In Upper Nene, wells failed in mid-August for the first time since 1868. Springs in the Cirencester area were only full for last 10 days of December and a shortage of water was severely felt (River Churn). Wells in valley dried up (Chew Valley) yet wells near summits flowing. • Dried up rivers (e.g., River Wallop, Hampshire, Herefordshire). • Ground subsidence, fissuring reported in Weald area, Sussex. • Bad heath and forest fires in Farnham, Hampshire. • 'The [Ingoldsby, Lincolnshire] parish council, to prevent any waste of water, have decided to dole out water to the parishioners twice a day' in August (River Glen). • Agricultural drought with land baked dry. Hay crop was the worst known for the previous 70 years. Most of the pastures reserved for hay were not worth cutting, the grass having failed to grow. Many of the root crops failed altogether, and in others the roots were not half the usual size. Many meadows were dried up in the summer (Alde, Sussex). • Much difficulty was experienced in watering stock(Herefordshire). • Large areas were artificially irrigated by pumping from the river Avon (Evesham).
1890-1909	Long drought (see next six entries)	Southern Britain?	

1908-1909	Summer 1908 to summer 1909	English Lowlands	Drought was preceded and followed by exceptionally wet periods. • Reports of intermittent stream (King's Sombourne stream) in Hampshire ceasing to flow in August 1908 and remaining dry until the end of October, and of dry streams in Little Ouse headwaters in December 1909. • Dry springs in Gwent in May and June 1909, also in Denbighshire (Clwyd headwaters) June–September. • Some water supply problems, such as in August 1909 in Leicester, quoting *The Times*, 'In consequence of the low state of the reservoirs of the borough, the Water Committee of the Leicester Corporation decided last evening to restrict the supply from 6 in the morning to 8 at night. The reservoirs have not been so low for some years.'
1904-1906	Spring 1904 to autumn 1906	All regions	• Mainly GW impact with reports of wells drying up and springs failing in 1904, summer 1905 and in 1906, such as in Tunbridge Wells, Adderbury (Oxfordshire – 'Great scarcity of water during the latter part of the year, many deep wells being quite dry'), Breconshire, Teme valley and Willingham-By-Stow (Lincolnshire). In 1905 failed springs and dried up ponds reported in Suffolk, Herefordshire (lowest spring flow for 35 years), springs failing in Derbyshire, some for the first time, also in Harrogate area and East Yorkshire Wolds, and Cherwell (Oxfordshire) in 1906. • Water supply problems reported in Sudbury and Gloucestershire, 'Water was scarce everywhere in the neighbourhood; in some villages it had to be fetched from a distance for drinking purposes, and in this place we were obliged to carry it in carts for the cattle ...'. Carting of water necessary in Tunbridge Wells area, 1904. • 1905, 'Owing to the dryness of the season the traffic at the upper end of the Dearne and Dove Canal was stopped for months, and at the lower end a full cargo could not be taken' (River Don). • 1905, Glyn Neath, Breconshire, noted, 'The Works here are entirely dependent on water, and the shortage in the summer months interfered considerably with business.'
1901-1902	Late winter 1901 to late autumn 1902	Large spatial variations	• Numerous reports of springs and wells low throughout period (many lower than in living memory) or failing completely (e.g., Kent; Sussex, Essex, Usk, Oxfordshire, Surrey, Severn, Avon, Isle of Man). 'At Detling chalk well in Kent from December 1901 until February 1903. The water level remained almost stationary near the bottom of the well.' East Anglia, 'exceptionally dry, ponds being very low and wells failing in many places' (Great Ouse). 1902 April Ipswich, 'Drought was becoming very serious at the close.' • 1902 Fish deaths reported in dried up pond on River Cray, Kent, which remained dry throughout 1903. • Head of River Lea recessed by more than 2 miles.

1898	Autumn 1897 to winter 1898	Southern Britain	Very dry 4 years, hence GW resources depleted. Many surface supplies were dry for the first time in 50 years. **1898:** • Chertsey (Thames), 'drought more destructive to trees and shrubs than in any other year.' • Low or dry springs, ponds and rivers – Sussex, Thames, Northumberland (Coquet), Chertsey (Thames). • 'General failure of the wells in the chalk' (River Pang). • 'Many wells had to be deepened, owing to the failure of springs.' • Norfolk, 'In many cases water had to be carted.' • 'In the early part of the year and throughout the summer the Usk was very low and in anything but a sanitary condition.' **1899:** • Ponds and wells ran dry in Wales (River Tawe), Sussex, Great Ouse, Thames. • Water being sold in Sussex for sixpence a bucket! • The destruction of rhododendrons was phenomenal, many dying from drought (Isle of Wight). • Water had to be hauled for cattle for the last five months (Thames valley and Oxfordshire).
1893-1996	Varies with region	Midlands and south	**1893:** spring and early summer exceptionally dry as regards severity and duration.[17] • Thames water had to be carted for cattle in December. • 'Owing to severe drought, the proprietors of several mills [in Dukinfield] that depend on the river Tame for a water supply have had some difficulties in keeping their engines running; indeed some slight stoppages have been occasioned at the mill of the Waterside Spinning Co. and others.' • Horncastle, Lincolnshire, '... during the long spell of dry weather in April 1893, the bed of the navigation canal was a favourite playground for children.' • No drought impacts recorded.[17] **1894:** • Reports that River Thames lower than in 1887, which until then was regarded as a record year, some said lowest level reached by the river since 1826. **1895**: severe cold January to March, then dry late spring to mid July. • Main impact on agriculture with very low yields in hay, straw, roots in Sussex, Kent, Ouse (River Whitewater) and poor-quality hops (Kent). 'The worst year for agriculture in the memory of the oldest inhabitant … and everything dried up' (River Whitewater). • Low GW levels and pond levels reported in September–December in Suffolk, Surrey. • Low wells and springs reported. • Early harvest (almost as early as in 1868), 'grass land quite burnt up and land caked hard to 9 inch depth' (Surrey).

1890-1991	Late 1889 to summer 1891	North and South	In southern England, Midlands and Welsh borders: • Many reports of dried up rivers (e.g., River Lambourne from September 1890; Great Malvern, 'The brooks and the river Teme were nearly dry for a great part of the year and at the close the whole district was short of water.'). • Many failed or exceptionally low wells. For example, December 1890 Hungerford, 'Nearly all the wells were dry at the close and had been so for two or three months'; 1890 Hampshire, 'At the close of the year the wells were getting dry, one well which had never been known to fail before, had been dry for some time';, 1890 Wiltshire, 'In the deep well in the chalk which supplies Devizes Waterworks, the water is now 98 feet from the surface and can be pumped out in a few hours'; summer 1891 Hungerford, 'Great scarcity of water in wells from October, 1890, to the end of September, 1891'; 1891 Pang, Berkshire, 'The unusually dry February caused a great scarcity of water, most of the chalk wells and streams being dry till November; then the abundant autumnal rain caused a good flow in each case, but seriously hindered the harvest.' • Water scarcity reported in 1890 in Berkshire, Tunbridge Wells, Kent, Gloucester and Mansfield. For example, 'Gloucester experienced a water famine and water from the Severn had to be used'; Mansfield, 'There was scarcity of water, the town being put by the water company on short allowance ... The fourth successive year with rain below the average of twenty years ... '. • Failed springs or reduced spring flow reported in Thames valley, River Dee, North Wales, Severn and Usk regions. For example, Assenton, near Henley, December 1890, '… lower than it had been for 26 years'; Stanton St John's, Oxfordshire, 'The springs were lower at the close than they had been for 11 years ...'; Newnham-on-Severn noted, 'Exceptionally dry, especially during the last 5 months, so much so, that wells and springs never known to fail before, had been dry for a long period at the close of the year'. In Anglia: • 1890 December, Nene group reported, '... ponds were still empty at the close of the year.' • 1890 November, Great Ouse group reported, 'Ponds, wells and springs were low all year, particularly so in November and December. ... it was necessary to cart water for stock in December.' • 1890 December, 'The water in the reservoir belonging to Boston Water works at Miningsby was, at the close of the year, lower than it had ever been before.'

1887-1888	Late winter 1887 to summer 1888 1887 was lowest rainfall from1868 to 1924 across much of the English Lake District and Pennines	West and north	• Low river and well levels reported in the south-west and Oxfordshire. For example, River Kenwyn (Truro Flour Mills); River Ems?; Torquay, 'There was a great scarcity of water until Oct 26th, many wells and streams, that were never known to fail before, were dried up'; 1887 November, 'Wells failing'; Banbury (Cherwell), 'Springs and mill streams were low at the close, and the rain had not penetrated to the depth of the plough'; July rainfall observer at Hutton Roof noted, 'Ponds dry for a longer time than can be remembered before by the oldest inhabitants. Comparisons were frequently made with the great drought of 1826 … at Maresfield, south of the Ashdown Forest, Kent, threepence a pail was paid for water during 1887'.[17] • Water supply problems in north-west, because of low reservoir levels across Pennines, 'The capacity of those schemes which were in operation during 1887 was more severely taxed than in those of forty subsequent years ...';[18]; Lake Derwentwater fell on July 9th to a lower level than ever previously recorded';[18] quotation dated August 27th, 'In spite of the rain which fell a week ago people residing in Langho, near Blackburn are suffering from water famine. All the water used has to be brought from Clitheroe by rail, in milk-cans and it is served out to the people by the stationmaster, who allows a bucket to each family. Beyond this there is not a drop of water in the district';[18] September 1st reports that water supply in Manchester is cut off during the nights;[19] December 6th reports from *Sheffield Independent* that Liverpool is in danger of a water famine … The District supplied by Liverpool Corporation, including the City and a number of surrounding villages, is to be put on short allowance'.[19] In Wales (e.g., Llechryd), 'Water supply almost failed';" 'At Barry, Glamorgan water is selling at 1/2d a bucket.'[19] • 1887 August, 4000 quarry men in North Wales were thrown out of work owing to the failure of streams supplying the quarries (River Seiont). About 1000 men were thrown out of Llanelly tin works owing to the supply from Cwmlledi reservoir being stopped.[19] • Typhoid fever broke out at Mountain Ash, Wales, attributed to drought and bad drainage (August 16th).[19] • Poor water quality of rivers in Devon, such as 'Owing to the long drought the river Lowman at Tiverton and the Exe at Exeter became dreadfully foul; in fact the latter was described as little better than a sewer.'[19] • Problems getting water for cattle, such as at Shap, '... water was hardly to be got for cattle, most of the wells being dry'; 'The Cheshire pastures are so dry that the cattle have to be stall fed as in winter … many cows have gone dry and the make of cheese will be 25% below average.'[19] Fens and River Nene, 'Good water has to be fetched from long distances.'[19] • Agricultural damage, such as at Llechryd, Wales, 'Vegetation suffered severely, grass and other things being scorched up, and fruit not swelling and ripening'; Newmarket, East Anglia, 'Exceptionally dry and hot. Vegetation on dry soils suffered from drought'; East Layton, near Darlington, 'Very hot and generally dry ... pastures sadly burned in places, but springs holding out well'; 'June 29th … In Cumberland and Westmorland the pastures are so burned up that farmers are selling their cattle at a sacrifice';[19] 'July 4th … The Thirsk district is in a fearful state, some scores of pumps are dry and

			pastures have scarcely a blade of grass'.[19]
1884-1885	Early 1884 to late 1885 (spatially variable)	Northern and southern England	• Lot of reports of failed springs and wells in 1884 (and to a lesser extent 1885) from across England and Wales with many lowest in living memory, such as Carisbroke Castle, Isle of Wight, 'well dried up during November … It is reported that it has not been dry before for 140 years'; Bodmin, 'Never before, perhaps, in North Cornwall were the fresh water springs so low, which caused a great amount of inconvenience. Bodmin spring failed for the first time for at least 38 years ... The springs were lower in November than for more than 80 years'; Doncaster, '… a well-sinker 70 years of age says that he this year saw ditches, ponds, and streams dry, which he had never seen dry before. Since 1868 the well here has not been so low before'. Yet reports of springs holding out well in Lincolnshire as heavy rain in July 1884 percolated through deep cracks, giving quicker recharge than normal. • Dry or exceptionally low rivers reported, such as River Rother in East Sussex was nearly dry; river Medway in Kent 'was very low, and all through the summer and autumn the water was much clearer than usual'; Teme river (Severn) was lower than can be remembered for 40 years; River Lambourne, Berkshire, on chalk ceased running in mid-October in 1884 and 1885; River Teign, Devon. • Mills affected in 1884, e.g., 'The miller in Cocking was for two months unable to grind, except for about one hour in 24, although his mill is situated on a stream issuing from the South Downs, which usually gives a plentiful supply of water at all seasons' (West Sussex Rother); Andover, Hampshire, 'mill-stream lower than it had been for 30 years previously'. • Water supply of many towns and villages was short, such as low reservoir supplies in Cheltenham and Northampton, 'The town was on short supply of water during a great part of the year – from 7 to 10 in the summer months, and 6 to 12 at the end of the year'; Loughborough, 'The reservoir at Nan Panton [*sic*] having ceased to yield a supply for the town, water was pumped into the mains from Burleigh Brook'; Tredegar, South Wales, '… town was on short supply for some months'; Oakham (Soar), 'Exceptionally dry. The pumps of the village, supplied by springs, were useless for more than a month – a circumstance not remembered by the oldest inhabitant'; River Darwen, Lancashire, 'The driest year of 12 recorded here … The large reservoir was very low, containing towards the close of November only four or five days' supply; the public were warned against "waste of water"'. • Low river levels in River Teign, Devon, 'interferred materially with salmon fishing.' • 1884 December Spalding (Pode Hole), 'One of the most remarkable years in the history of Fen drainage; at the close of the year the engines were standing still, and the water in Deeping Fen was allowed to rise to almost summer level to afford a supply for cattle and in case of fire etc.' • Water was sold for months at a halfpenny a bucket, wells and springs being dry (Hull area); Beverley, North Yorkshire, 'All ponds and wells dry, and farmers had to buy water of the company, or from some other source, until December.'
1874-1875	Late 1873 to	English	• 1874 July, Strathfield Turgiss, Hampshire, '... ground parched, clover shrivelled for want of rain, enormous cracks in meadow from dryness of the soil, by the 12th the wells were beginning to fail, by the end of the month the cracks in the

	early 1875	Lowlands	meadows sufficiently wide for small birds to fall in and be unable to get out, and the river very low' (River Loddon). • 1874 August, Diss, Norfolk, '... the want of water, however, is severely felt in the neighbouring villages, and its scarcity, together with defective drainage, has caused the air of our town to become most offensive, our small river being nearly stagnant, and the water black, filthy, and polluted ...' (River Waveney). • Reports of vegetation dying in July 1874 in Cambridge; Compton Bassett, Wiltshire, 'Pastures burnt up'; Wem Salop, Shropshire, '... many forest trees are dying ...'. • 1874 July, Compton Bassett, Wiltshire, 'Water has become so scarce that it has to be carted from a distance for the use of the sheep and cattle.'
1870	Spring 1869 to summer 1871	All regions	Hot dry summer 1870, in Kendal district, July to September drought was equalled only in 1913 during past 108 years; Seathwaite had lowest summer 2 month rainfall from 1845-1894. Yet fewer reports of drought impact than in 1874 and 1875. • Springs low and some wells dry from Scotland to Devon. • Water shortages reported, such as 1870, November, Totnes, Devon, 'The past summer has been the driest ever remembered in Totnes … great scarcity of water, the town supply only an hour or so daily, and to private consumers only twice a week. The springs did not break till the latter part of November'; 1871, September, Menai Straits area of North Wales, '... water supply yet rather deficient along Menai Straits, sources that cease in June or July, and usually revive in August being yet dry'. • Reports of deficient hay crops in summer 1870 in Exe catchment, Devon, and in North Wales. • Very low river levels, such as 1871 Marlborough, 'In 1871 it was necessary to cleanse the whole river, a job which had not been done for several years ...' (River Kennet); 1870, 'The Wye was recently in places almost invisible, and easily crossed on foot ...'. • 1871 December an observer for Uckfield noted, 'About the middle of December, water was very scarce, and nearly all the water-mills were at a stand-still' (Sussex Ouse). • Observer at Ulverstone, Lake District, noted, '... whilst in the greater part of Yorkshire, and I believe in most of the central counties, the crops were literally burnt up, in our vicinity and generally west of the mountain range, grass and most other produce were above the average, the former remarkably so.' • 1870 December, 'Imber: Many wells in this parish were dry from the end of October to the beginning of 1871' (River Wylye).

1869	Spring to winter	Most regions	• Failure of wells in Upper Nene (Orlingbury); Aston Rowant, Buckinghamshire, '1869 the driest for many years past; wells have been dry in the neighbourhood, that I have never known to fail before'; Northampton (Thame tributary), '… springs quite as low in November as in the previous year ...'. • Reports of springs failing in Devon in 1869, such as Great Torrington, 'The springs began to fail much earlier in 1869 than in 1868 ...'; Bodmin, 'The drought in July, August and September was unexampled' (River Camel).
1867-1868	Autumn 1867 to late 1868	North-west	• Major water supply problems and restrictions on use in the north-west in 1868, such as: i. 'At Preston the reservoir became practically dry at the end of August, and costly pumping works were hastily established, which were required for 58 days.' ii. 'In Manchester ... the corporation, on the 3rd of August, limited the supply to the city to 12 hours per day, stopped the street watering, and diminished the trade supplies by half. They also made an arrangement with the millowners for reducing by one half the quantity given to the mills on the line of the river, and made compensation in money for the deficiency. In the middle of September the general supply to the town was further limited to eight hours per day, and the quantity for trades also diminished. The eight hours' supply lasted seven days, and the 12 hours' supply 76 days. At Rochdale, as early as the 25th June, the supply was limited to four hours per day for 15 weeks; but with this precaution, during the second week in October the store became entirely exhausted, and the town would have been almost without water but that recourse was had to pumping from a colliery in the neighbourhood. At Bury the store ran so low towards the end of August that it was reserved entirely for compensation to the mills, and the company obtained a supply of seven gallons per head from neighbouring works; for baths and for numerous manufacturing and trade uses in the town there was none. This continued for five weeks.' iii. 'At Halifax the reduction began on the 11th of May; the domestic supply was limited to 14 hours per day for 66 days, to 10 hours for 10 days, and to six hours per day for 86 days; the supply to large consumers being gradually reduced from 30,000 to 1,000 gallons per day.' iv. 'At Sheffield the supplies were first reduced in June, and further in July, August, and September, the last reduction being to four hours per day.' v. August 3 *The Times* is quoted, 'Windermere Lake is, at this date ... 7 ft. 2 in. lower than the highest high-water mark, and that notwithstanding ... the advantage of a considerable body of water let out of Stickle Tarn to supply the [gun]powder works at Elterwater.'

1863-1865	Late 1863 to autumn 1865, especially in 1864	Western Britain	• Agricultural drought with pasture burnt up in Cornwall, and across the Midlands, clay soils cracked two or three feet deep in Worcester, Hereford, and Gloucester, where 'the pastures were perfectly brown; the pools and watercourses dry; the rivers, also, unprecedently low.' 'In Yorkshire, especially in Holderness, the drought began to assume serious proportions, there being no grass and no water.' • Low river levels (e.g., River Don, Rivers Severn and Wye) and in Lincolnshire October 1864 quote from *The Times*, 'During the recent drought, on account of its being rather over-drained, Lincolnshire has suffered more from scarcity of water than many other counties; for leagues round Boston not a drop could be found in ditch or furrow, and most of the smaller drains were dried up ...' (Witham). • Some springs failing (e.g.) Malvern). • Water supply problems, such as water more scarce in Cornwall than for past 20 years, 'scores of men are employed in carting water from the different rivers. In Camborne the evil is much felt, also in Redruth, where the reservoirs are so nearly empty that the town is on short supply. In Truro, where usually water in abundance runs to waste through the streets, its want is severely felt, the public and private pumps being almost exhausted; men are at work sinking the public pumps to greater depth.' Water shortages also reported in Nottinghamshire, Derby, Lincoln, and Leicester. • 'In South Wales, many hundred hands were thrown out of employ at the iron, tin-plate and coal works, there not being enough water to keep the works going, even at half time; but the pasture were beautiful compared with the adjacent counties.' • July 1864, 'In the neighbourhood of Southampton, trees twenty or more years old were visibly suffering from the drought, so deep had it reached.' 1864, Rhyader, Wales, 'No supply of salmon, owing to very low state of the Wye.'
1854-1860	Long drought (see next two entries)		

1858-1859	Autumn 1857 to early 1859	National	• 1859 March, concerning the family paper factory on the spring-fed River Gade in the Chilterns, 'We are just now overwhelmed with orders and have no water wherewith to make them ...'. • Streams in Little Ouse headwaters dry from 1859 to 1862. • In 1858, 'The Great Stink' (http://www.the-river-thames.co.uk/environ.htm) from the polluted River Thames caused thousands to flee the City, while Parliament remained in session. Windows of the parliament building were draped with curtains soaked in chloride of lime, to prevent closing of the Government. Upper class residents fled the city or drenched sheets with perfumes to mask the odour from the outside.
1854-1855	Autumn 1853 to late 1855	National	Second most severe consecutive 18 month England and Wales rainfall drought between 1820 and 1976, ending May 1855; Central Lake District (Grasmere, High Close), lowest calendar rainfall in about 200 years to year 2000 – 1139 mm (and within a very dry era, 1853 to 1858); 1854 Chilgrove, West Sussex, 'The year 1854 was the driest in the record [1836-1919] being only 21.81 in. or 36 per cent in defect of the average …. 'lasted almost without a break until the end of September, 1855, a period of 23 months.' • 1854 July 19, '... the well at Milebarn was dry, and the Gade rose two miles and a half lower down the valley, than its ordinary source during the period of full water.' • Bristol Water Company, 'A drought, unexampled for nearly sixty years set in, and from May to October the supply of water to the city was very limited, much to the wrath of the consumers.' • 1855 an observer at Lambourne, Berkshire, remarked, 'According to tradition there was a drought here in 1855, when only three wells yielded water, since when some of the wells have been deepened.' • Poor water quality in the upper estuary of the Thames was attributed to the drought in the two preceding years. Clutterbuck noted that, 'In May [1855], the river was in a most filthy condition, which was ... in his opinion ... rather due to a defalcation in the "perennial flow" ... inasmuch as in the eighteen months ending April 1855, only 23.5 inches of rain had fallen, that being the average for twelve months. The perennial flow, especially in the upper districts, before the river received the larger streams flowing from the chalk, was never, in the memory of man, so much reduced. The Surveyor of the Thames Navigation had informed him, that they were enabled to open all the flood-gates of the Pangbourne lock, at one time; a fact without example in his remembrance ... The Cherwell ... was ... (May 1855) so reduced in volume, that it was deemed necessary to contrive a dam to flush the bed of the stream. He had never, from his own observations, known the stock of water in the chalk stratum to have been so low, nor the perennial flow of the streams issuing from it, to have been so reduced.'

1851-1852			• Reference to diminished supply and deteriorating water quality in River Aire during summer of 1851. • In the Anglia region, 1851, 'one of the largest southern lakes, Whittlesea Mere has finally disappeared from the map.' • Chilgrove chalk well, Sussex, 'water level at end of 1851 dropped below level of silt at bottom of well and did not reappear until following February.' • 1852 Lavant, Sussex, 'scarcely enough water in the Lavant to wash the sheep'; also reports of many springs dry in Sussex, 'which were never known to be so before'. • Report of Metropolitan Water Supply (Thames) Enquiry refers to 1852 drought.
1844-1845	Spring 1844 to spring 1845		• Trent: Oakham Canal to be closed for lack of water for 5 months. • Cholera outbreaks in many UK cities in 1840s.
1826-1827	Spring 1826 to autumn 1827	National	• 1826 references to crop losses through hot dry conditions, such as Upper Windrush, Cotswolds, 'The long continued drought is remarkable; the hay made during this season is excellent in quality but very deficient in quantity; the springs are exceedingly low, the wheat looks promising but the barley and oats thirst for rain; the pastures are sadly burnt and the promise of turnips is sadly small.' • 1826 *Annual Review* (England and Scotland) states that the heat and drought 'threatened an absolute dearth in other species of grain [than wheat], as well as in pulse and potatoes. Barley was far from reaching the extent of an average crop; but it was in oats and pulse that the apprehended scarcity was most alarming. The accounts from every part of the country were equally unfavourable ... violent and continued heats were so prejudicial to grass that, on the richest meadow lands of England, it became necessary to feed cattle with dry fodder, almost as in the depth of winter.' • 'Derwentwater 14th June 1824, the water at that time being thought to be unusually low, a permanent notch was cut in the rock of Friar's Crag, which I call zero. On the 5th of July 1826, the water was 6 inches below; but this might in part be accounted for by the state of the outlet ...'
1814	Winter to summer	Northern England	Notable dry 30 month period at Carlisle ending 30 September 1814. Winter of 1814 cold and dry with extensive snow falls. No evidence of impact.
1802-1803	January 1802 to late 1803	National	1803 October 24, 'Most of the village [Over Stowey, Quantocks] coming to my well for water, never was such a scarcity before.'

Note: BHS Chronology and internet searches were made for all events even where no impacts found. BHS Chronology is the primary source for impacts unless other source quoted, as in notes below.

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List of abbreviations

BHS	British Hydrological Society
CEH	Centre for Ecology and Hydrology
CET	Central England temperature series
CLD	Central Lake District
CRU	Climatic Research Unit, University of East Anglia
EMID	East Midlands
E&W	England and Wales
GW	Groundwater
NRFA	National River Flow Archive
SW	Surface water (river flows)

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