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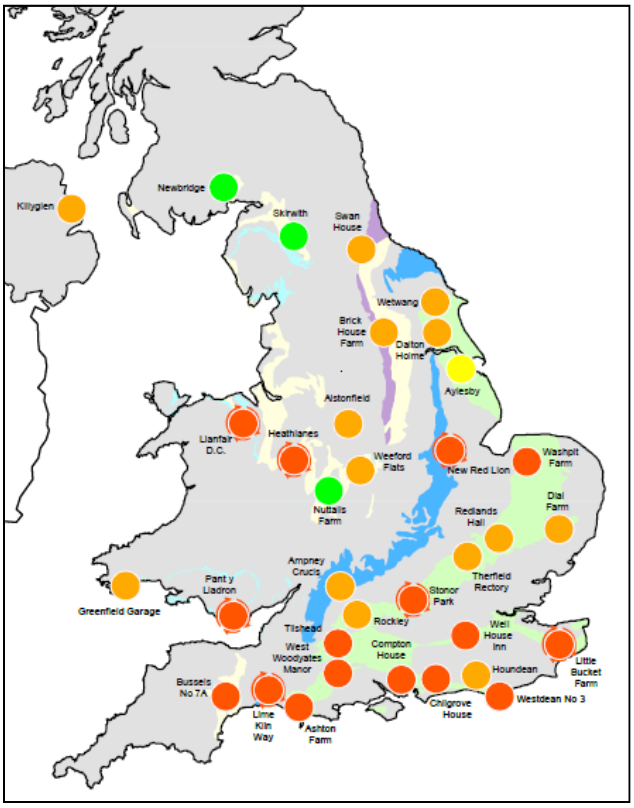
Description of groundwater droughts in the UK: 1890 to 2015

Groundwater Science Directorate

Open Report OR/15/007



BRITISH GEOLOGICAL SURVEY

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Front cover

Map showing status of groundwater levels at Index Boreholes in March 2012. ©NERC 2012.

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Foreword

Droughts pose a threat to lives and livelihoods in many parts of the world and may also cause significant problems in temperate areas, including in the UK; a humid country, but one marked by significant regional and temporal/inter-annual variations in rainfall. For example, the recent UK drought of 2010-2012 (Kendon et al., 2013) exemplified many of these challenges. Despite its unusually abrupt termination, the drought had major impacts on agriculture, the environment and recreation, and was the focus of extensive media and public debate.

As part of a NERC directed programme on Drought and Water Scarcity in the UK (http://www.nerc.ac.uk/research/funded/programmes/droughts/), a project to investigate and characterise episodes of historic drought and water scarcity in the UK using a systems-based study of drivers and impacts was awarded to a consortium led by the Centre for Ecology and Hydrolgy (CEH) and including the BGS. The project started in 2014 and will run until 2018. One of the aims of the study is to develop an inventory of droughts, including groundwater droughts, in the UK.

This BGS report is the first contribution to the development of such an inventory and builds on the work of Bloomfield and Marchant (2013) who through development of the Standardised Groundwater level Index (SGI) were the first to systematically document groundwater droughts in the UK using groundwater level time series since the late 19th C. In this report groundwater drought events identified in those time series are explored further by placing them in the hydro-meteorological context and by describing their impacts as recorded in the literature of the time and subsequently.

The work described in this report was undertaken by Mason Durant in January 2015 as part of Research Assistant placement with BGS Groundwater Science Directorate, Wallingford.

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Data on UK precipitation has been derived from The Met Office Hadley Centre, ***www.metoffice.gov.uk/hadobs.***

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Summary

The UK has experienced several, in some instances, prolonged drought episodes since 1890. This report summarises the major historical drought periods in the UK with respect to groundwater, from 1890 to 2012. The Standardised Groundwater level Index, SGI (Bloomfield and Marchant, 2013), for Chilgrove House (taken to broadly representative of groundwater droughts in southern UK) and Dalton Holme (taken to be broadly representative of northern UK) have been used to identify and characterise the drought episodes. The report consists of 9 descriptions of episodes of drought in a standard form, as well as a summary, and in some cases an analysis, of the literature available. Comparison of drought events is possible using the drought classification and summary found in each standardised description. Key sources of information include British Geological Survey (BGS) and Centre for Ecology and Hydrology (CEH) drought summaries post-1976, as well as long borehole records, meteorological and hydrological data and reports.

The compilation of the descriptions has highlighted discrepancies in the literature and data covering some periods, with a tendency for underreporting of earlier events, as well as those that displayed limited surface water impacts. In addition, a comparison between hydrological and meteorological reports and the SGI and groundwater data indicated differences in the reporting of the 2003-2006 drought and the 1988-1998 period. While general trends and characteristics are apparent for all the major UK droughts, each event typically exhibits unique features. In an attempt to develop a broad classification based on event characteristics, a matrix is presented based on parameters important to groundwater drought and this has enabled different drought patterns or typologies to be explored. For example, from the matrix it has been noted that, at least for the period under consideration, northerly groundwater droughts typically consist of a single winter event and tend to be underreported in the literature, despite relatively high intensity.

1 Introduction

The UK has experienced several, in some instances, prolonged drought episodes since 1890. Many of the more recent droughts have been documented in detail, but for earlier droughts, especially before 1976, the records can be fragmentary. Much of the published literature has concentrated on the meteorological aspects of drought, or the consequent impacts of drought on economic activity, in particular agriculture and water supply. The effects of drought on groundwater have not been systematically documented in the same detail.

Bloomfield and Marchant (2013) developed an index for standardising groundwater level time series and characterising groundwater droughts, the Standardised Groundwater level Index (SGI), and calculated SGI for 14 relatively long, up to 103 years, groundwater hydrographs from a variety of aquifers, including Chilgrove House and Dalton Holme. Here we have used the SGI time series for these two sites as the basis of the current investigation of the groundwater drought history of the UK.

SGI is a non-parametric normalization (the normal scores transform) of data that assigns a value to observations, in this case monthly groundwater levels, based on their rank within a dataset, in this case groundwater levels for a given month from a given hydrograph. When SGI is negative it indicates drought conditions and the more negative it is the more intense the drought. The normalised SGI values can be compared between sites over similar time periods to characterise the relative intensity of a drought between sites. More details about how SGI is calculated can be found in Bloomfield & Marchant (2013).

The 9 groundwater drought episodes described in this report have been identified by analysing the SGI time series for Chilgrove House and Dalton Holme from Bloomfield and Marchant (2013), i.e. for dates between 1910 and 2006. For each SGI time series a drought event is defined as any period where consecutive months are negative; a drought ends when SGI returns to a positive value. For each drought event, a total drought intensity can be estimated from the cumulative negative SGI over the drought event. In addition, the average intensity of the event can also be estimated by dividing the total intensity by the number of months of drought. Total and average drought intensities for all drought events in the Chilgrove House and Dalton Holme SGI time series have been estimated. Table 1 below shows the total and average SGI intensities for the seven most intense droughts (based on the average SGI where average drought SGI is <-1) in the record. The most intense drought event at each site is highlighted in yellow. In addition, it can be seen from Table 1 that the impact of drought episodes is not equally experienced at both sites and only sites where the average drought SGI is <-1 are highlighted on bold.

The drought events listed in Table 1, along with the drought known as the ‘long drought’ of 1890 to 1910 (Marsh *et al*., 2007) and the drought of 2011 to 2012 (Marsh et al., 2013) - both identified as a major drought episodes but outside the scope of the SGI record of Bloomfield and Marchant (2013), are the focus of this report.

In summary, this report details the major historical drought periods in the UK with respect to groundwater, from 1890 to 2012. The report consists of 9 standardised drought descriptions containing details of the droughts, as well as a summary, and in some cases an analysis, of the literature available (see section 1.1 for details). The aim of the report is to enable comparison between drought events, and assess the possibility of creating a drought classification based on event characteristics. There is also an attempt to review the literature and the public and academic discourse surrounding each drought.

Table 1: Total and average SGI for drought episodes at Chilgrove House and Dalton Holme where average drought SGI is <-1.

Drought episode	Chilgrove House				Dalton Holme			
	Start	End	Total SGI	Av. SGI	Start	End	Total SGI	Av. SGI
1913 to 1914	Dec-13	Dec-14	2.32	0.17	Dec-13	Dec-14	**-15.48**	**-1.11**
1933 to 1935	Sep-33	Apr-35	**-27.23**	**-1.36**	Nov-34	Nov-35	-5.28	-0.41
1964 to 1965	Sep-64	Oct-65	-3.35	-0.24	Sep-64	Oct-65	**-18.26**	**-1.30**
1975 to 1976	Oct-75	Nov-76	**-25.27**	**-1.81**	Oct-75	Nov-76	**-17.21**	**-1.23**
1988 to 1993	Jul-88	Nov-93	-46.27	-0.71	Jul-88	Nov-93	**-99.3**	**-1.53**
1994 to 1998	Jul-95	Jan-98	**-38.83**	**-1.25**	Jun-94	Jan-98	**-54.33**	**-1.23**
2003 to 2006	May-03	Jan-06	**-37.72**	**-1.14**	May-03	Jan-06	-13.17	-0.40

1.1 METHODOLOGY

This methodology describes and explains the definitions contained within the drought descriptions. In order for coherent comparison between the 9 droughts, the drought descriptions, along with the start and end dates are presented in a consistent manner, as described below.

1.1.1 Definitions

There are many definitions and classifications of drought, and some recognised classes of drought include meteorological, agricultural and hydrological droughts (Tabony, 1977; Marsh *et al.*, 2007; Rodda and Marsh, 2011). The aim of this report is not to define drought or groundwater drought; rather it is to provide broad description of groundwater aspects of major drought episodes. The assumptions that have been made regarding identification of the drought episodes are explained below.

Dates

All dates referred to in the report under the headings of drought episode, start and end dates are applicable to groundwater, unless specified otherwise. These start and end dates are informed by the Standardised Groundwater Index (SGI; see Bloomfield & Marchant, 2013) except where not available (1890-1910, the year of 2006, 2010-2012). Dalton Holme and Chilgrove boreholes have been taken as proxies for the North and South of England respectively.

Start Date

Usually defined by a significant period of negative SGI but also informed by groundwater level reports and data in some instances. Meteorological dates have been included for context and comparison.

End Date

Groundwater drought terminations can be highly spatially and temporally variable and depend on local aquifer storage and flow properties (Bloomfield & Marchant, 2013) as well as hydrological processes (Tallaksen *et al.* 2009) and meteorological inputs. As a consequence, the end of a groundwater drought is particularly difficult to constrain. For the ease of comparison between episodes, end dates have been derived from the SGI (SGI values return to positive for a prolonged period of consecutive months) and groundwater reports where possible. Where these sources of information were not available, groundwater data has been used in a qualitative way to estimate end dates. Some interpretation was required in the observation of general trends. Meteorological dates have been included for context and comparison.

Drought Classification

The drought classification provides a description of each drought period based on:

A single or multi-winter event, groundwater start date, meteorological start date, regional or national focus, drought intensity using SGI where possible, other significant comments and termination characteristics.

This classification will be compared later in the report to look for common trends and patterns between events (see section 3.1.2).

Regional Characteristics

This section describes the spatial and temporal variability of the drought episode with respect to groundwater. Some context of pre- and post-event conditions is included, as well as any particularly relevant meteorological or hydrological background. These are both explained in greater detail in individual sections in each drought description.

Where possible, existing reports have been used to populate the standardised drought descriptions. These are referenced and can be referred to for greater detail on a particular episode. For droughts without an accompanying report, particularly older droughts, rainfall reports and data as well as hydrometric data were used alongside groundwater data when available. Anecdotal evidence was used only in the absence of this information. In addition, other relevant data and literature sources were used where appropriate.

Drivers and impacts

Following the description of the groundwater drought, each description also includes notes on the relationship with meteorological drivers and impacts of the drought, including surface water impacts, environmental, agricultural, economic and societal impacts and water resource management and regulatory responses to the drought episode.

Observation wells

The following observation wells are referred to in the inventory:

Table 2: Observation wells referenced in report

Well	**BGS Reference**	**NGR**	**Notes**
Chilgrove House	SU81/1	SU 8350 1430	Unconfined Chalk, longest continuous groundwater monitoring record. Hampshire.
Compton House	SU71/23	SU 7550 4900	Unconfined Chalk. Hampshire.
Therfield Rectory	TL33/4	TL 3330 3720	Unconfined Chalk. Hertfordshire
Dalton Holme	SE94/5	SE 9650 4530	Unconfined Chalk. Yorkshire

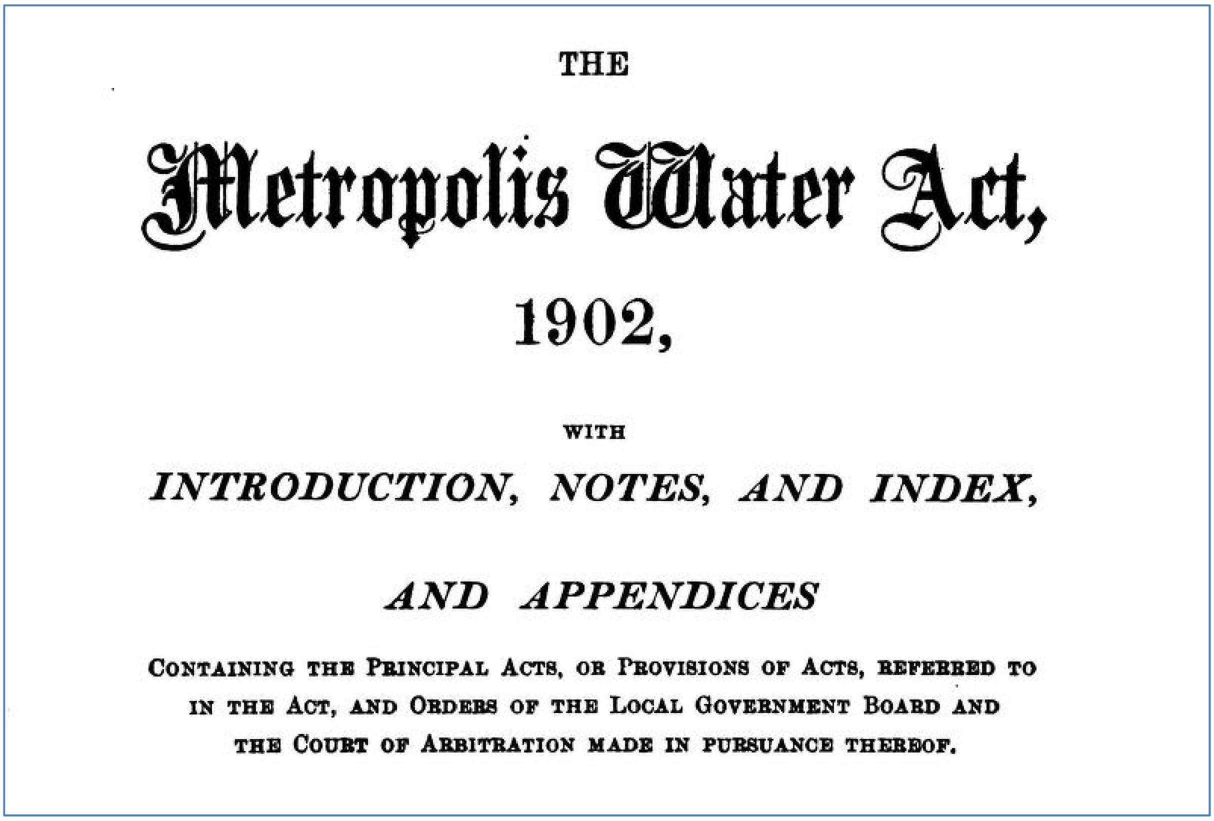
Further data on these wells can be found at :

http://www.bgs.ac.uk/research/groundwater/datainfo/levels/home.html

2 Description of the droughts

2.1 THE 1890 – 1910 DROUGHT, OR THE 'LONG DROUGHT'

"The Long Drought"


THE

Metropolis Water Act,

1902,

WITH

INTRODUCTION, NOTES, AND INDEX,

AND APPENDICES

CONTAINING THE PRINCIPAL ACTS, OR PROVISIONS OF ACTS, REFERRED TO IN THE ACT, AND ORDERS OF THE LOCAL GOVERNMENT BOARD AND THE COURT OF ARBITRATION MADE IN PURSUANCE THEREOF.

Figure 1: The frontispiece to the Metropolitan Water Act, 1902

2.1.1 Summary

The Long Drought is a period that is unrivalled in modern records in terms of its severe and sustained impacts on groundwater. The drought was characterised by a succession of dry winters, starting with winter 1890/91, and mainly affecting the English Lowlands. Particularly severe episodes include 1893, 1899, 1902 and 1905, while the wettest year on record at Kew was recorded in 1903. This spatially and temporally varied rainfall was also a characteristic during the end of the drought. There is very limited data and information on this period, with very few groundwater or hydrological monitoring stations. The lack of information is not considered to be due to a lack of severity or duration of the drought, and further investigation into this period is required.

2.1.2 Drought classification

Multi-winter event, a winter groundwater start, an autumn/winter meteorological start, focussed mainly in the English Lowlands but with impacts felt elsewhere over the course of the period, both intense and long, containing brief wet periods, spatially and temporally varied end to drought.

2.1.3 Graphical summary

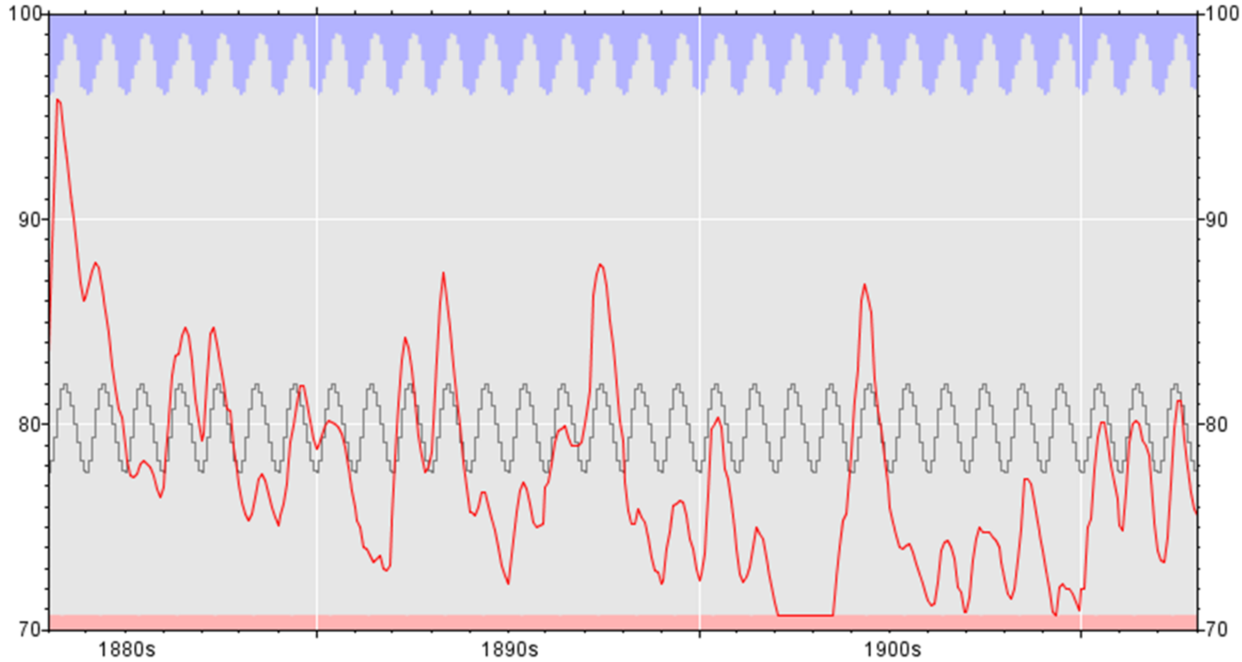


Figure 2: Therfield Rectory: Groundwater Levels during the 1890 - 1910 drought

2.1.4 Start date(s)

Winter 1890/91

The well level at Therfield Rectory indicates drought conditions during Winter 1890/91 (NGLA, 2015), supported by anecdotal evidence of well levels from the BHS Chronology. Rainfall deficiencies appear to start in September 1890 (Alexander & Jones, 2001).

2.1.5 End date(s)

Spring 1910

The well record at Therfield Rectory indicates a recovery above average levels by spring 1910 (NGLA, 2015). Rainfall was intermittent and spatially distributed throughout the drought end, and with limited information, the drought appears to end from a meteorological perspective in most areas in about winter 1909 (Mill, 1910).

2.1.6 Regional characteristics

The 1890-1910 drought was a prolonged period of drought, caused by long sequences of very dry winters. Due to the length of this drought, it would not be practical to discuss all events within the period. Instead, general trends, specific events and those discussed by Marsh *et al.* (2007) are included. The drought was particularly severe in the English Lowlands, with the succession of dry winters creating extremely low groundwater levels (Marsh *et al.* 2007). The drought had reasonably large spatial differences, with areas away from the South and East experiencing more attenuated impacts (Marsh *et al.* 2007; BHS Chronology). Available groundwater data from the period consists of four boreholes, of which only two cover the entire period and one starts the year before the drought. There are also hydrometric uncertainties associated with these data sets (NGLA, 2015). There is therefore exceptionally limited scope for assessing the regional characteristics of the drought. While the drought was mainly focussed on the English Lowlands, certain periods had greater severity in other regions, for example the lowest groundwater levels in Dalton Holme are observed in 1905, while this signal is not as strong in more southerly boreholes at Chilgrove House and Compton House (NGLA, 2015). In addition, Therfield Rectory well ran dry in 1902 and 1903 (see Figure 2 in section 2.1.3), while the record at Dalton Holme demonstrates levels well above minima (NGLA, 2015). The BHS Chronology provides limited anecdotal evidence of low spring and well levels throughout the period. There is no modern comparison to the Long Drought in terms of the succession of dry winters and the duration of groundwater depletion (Marsh *et al.* 2007).

2.1.7 Relationship with meteorological drivers

Due to the lack of groundwater information available for this period, most inferences made about this drought come from meteorological reports. There is a full record of these British Rainfall reports which can be accessed for complete details of rainfall. As previously stated, the impact of successive dry winters at the start of the period created drought conditions. This started with the driest September to April 1890/91 on record for England and Wales (Marsh *et al.* 2007). There is some evidence that the preceding winter was also extremely dry and acted as a precursor to the main event (Symons, 1890). Particularly dry winters followed in 1898, 1902, 1905 and 1909 (Marsh *et al.* 2007). The dynamics of such a long period of drought meant that alongside these extremely dry winters, 1902 was the wettest year on record at Kew (Marsh *et al.* 2007) caused by persistent cyclonic conditions (Mayes, 2004). This caused flooding while springs and wells were extremely depressed (BHS Chronology). Not only was rainfall temporally distributed, large spatial differences also occurred. The Lake District recorded above average rainfall for this 20 year period, while at Kew, only in 1903 was the long term average exceeded during the entire drought (Marsh *et al.* 2007). The drought broke with spatially and temporally varied rainfall throughout winter 1909 and 1910.

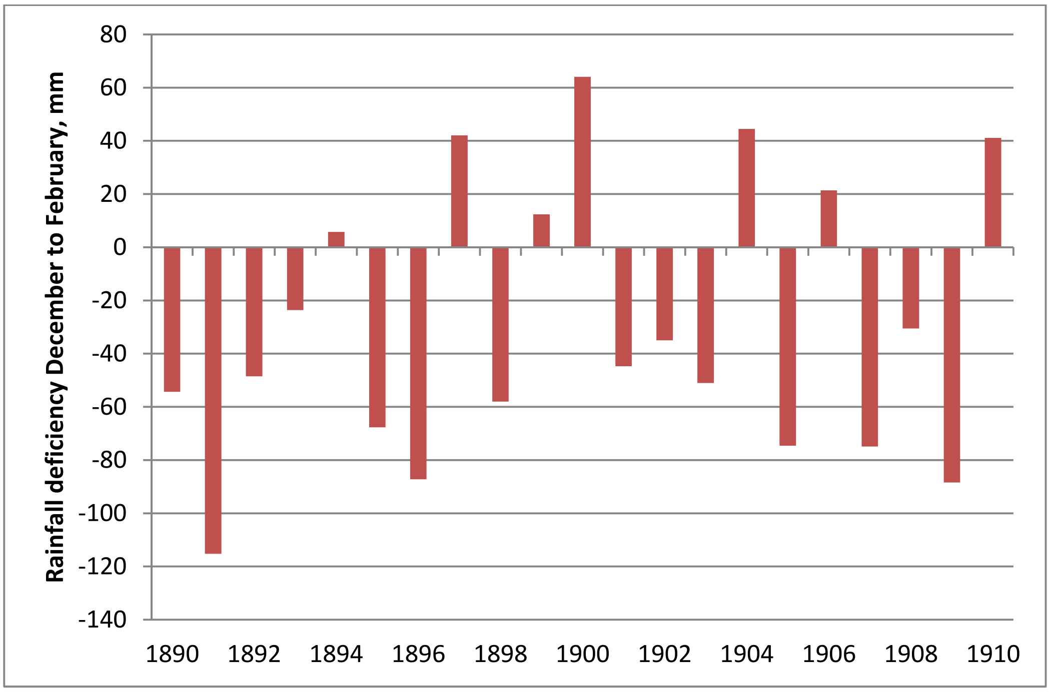


Figure 3: Rainfall Winter (Nov–Jan) rainfall deficiencies during the 'Long Drought' in South East England (*Data from Alexander et al, 2001*).

2.1.8 Relationship with surface water drought impacts

Streamflow measuring on the Thames at Kingston and the Lee at Feildes Weir are the only records from this period (NRFA, 2015). The only other evidence is anecdotal records supplied through the BHS Chronology. Both of these sources demonstrate the profound impact on river levels throughout the period, although due to the spatial distribution of these sources, little can be ascertained about any local variations.

2.1.9 Relationship with other environmental, agricultural, economic and social impacts

The impacts of the drought are not extensively reported, probably due to a lack of outlet for such observations. There are however reports in the BHS Chronology and Marsh *et al.* (2007) of severe impacts on agriculture and the occasional disruption of industrial productivity. There are well documented issues with water supply, particularly in rural areas (BHS Chronology).

2.1.10 Water resource management and legislative responses

There is a reference in the BHS Chronology to the limiting of supply by the water company at Mansfield in 1890, and Taylor *et al.* (2009) reports on rota cuts in areas of the East End of London during the summers of 1895, 1896 and 1898. Taylor *et al.* (2009) also comment that the droughts of this period highlighted the security in supply flexibility, with the Walthamstow reservoirs receiving compensation supply from other metropolitan companies after intervention from the Local Government Board. This was followed up by the Metropolis Water Act in 1899, which required improved communication between metropolitan companies and the emergency transfer of water when needed (Taylor *et al.* 2009). Water shortages experienced in the 1890s contributed to the pressure for municipalisation, which occurred in 1902 (Taylor *et al.* 2009).

2.2 THE 1913 – 1914 DROUGHT

December 1913 – December 1914

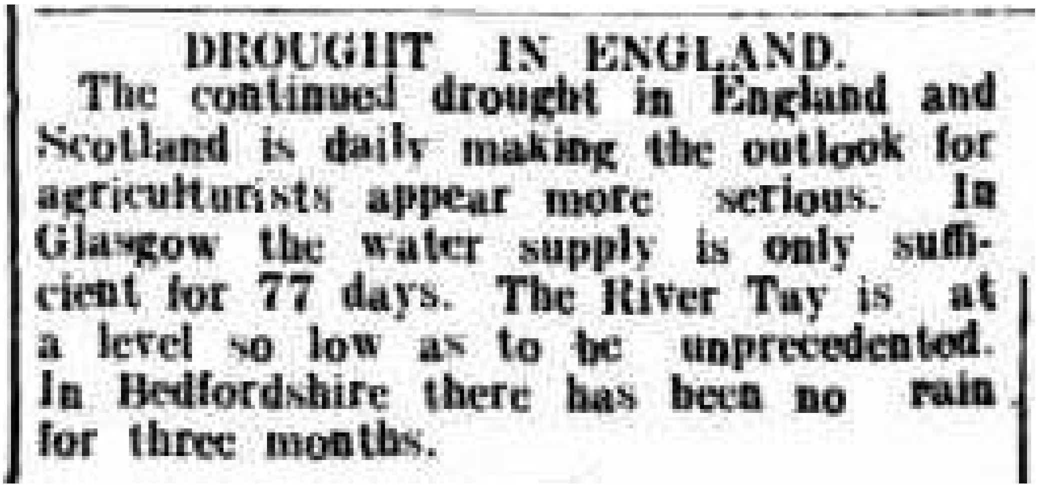

DROUGHT IN ENGLAND.
The continued drought in England and Scotland is daily making the outlook for agriculturists appear more serious. In Glasgow the water supply is only sufficient for 77 days. The River Tay is at a level so low as to be unprecedented. In Bedfordshire there has been no rain for three months.

Figure 4: Reporting of drought in an Australian newspaper, 1913.

2.2.1 Summary description

Investigation of the 1913-1914 drought reveals a lack of groundwater monitoring, agricultural, social and economic records about this period. More is noted of the thunderstorms in the summer of 1914 than the drought. Whether this is a reflection of monitoring networks and academic discourse of the time, the First World War or the impact of the drought itself is unclear. Drought periods were expressed on a threshold level and based on aridity, not groundwater impacts. Surface water impacts were low, shown by the lack of reporting in the literature. Although the Standardised Groundwater Index (SGI) intensity for Dalton Holme was lower than other major drought periods, this is not to say that the drought didn't have localised impacts on well yields. The drought was highly localised, limited mainly to the East of England. Dalton Holme borehole appears ideally located to pick up the strongest drought signal. A dry winter that affected these localised regions in the East, with dry summers either side that affected the whole of the South of England, propagated the drought. The drought intensified through the summer and autumn of 1914, when most impacts on agriculture were experienced, particularly in the South.

2.2.2 Drought classification

Single-winter event, winter groundwater start, early summer meteorological start, highly regional eastern focus, summer drought conditions spread drought to southern regions, SGI drought intensity of -1.11 for the North of England at Dalton Holme, increasing in intensity towards the end of the drought period, ending with unprecedented winter rainfall.

2.2.3 Graphical summary

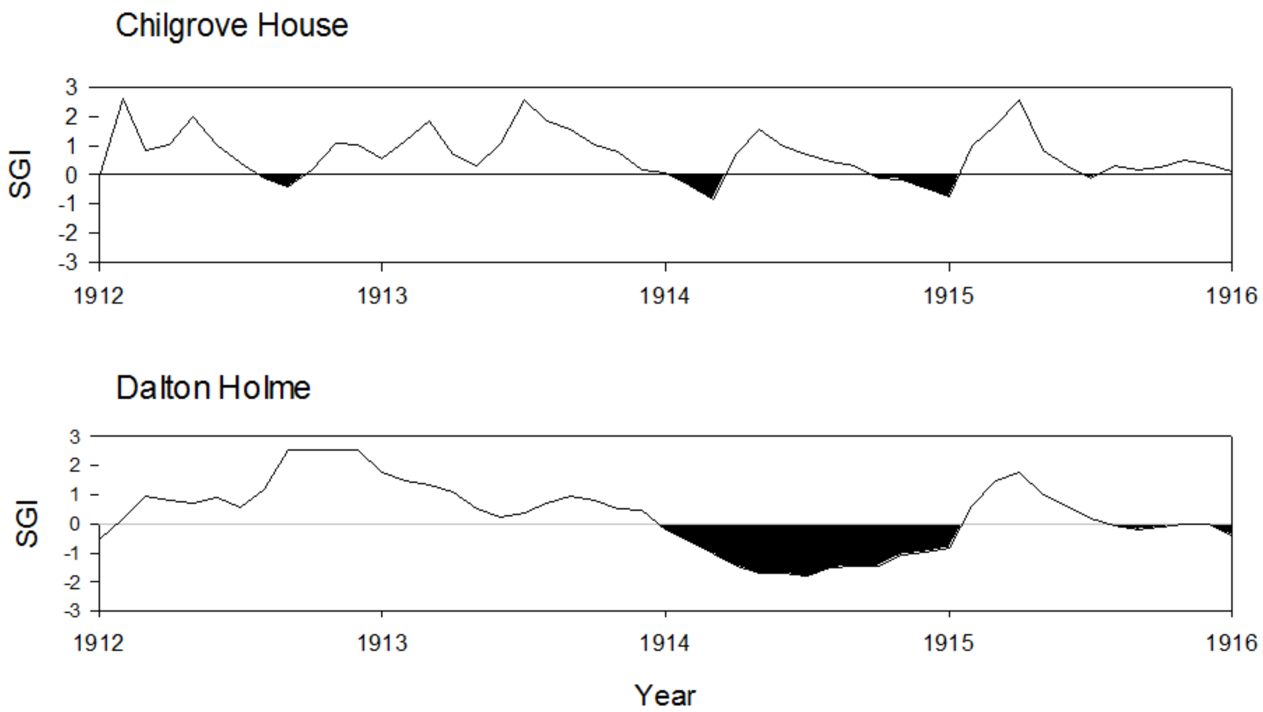


Figure 5: SGI time series from 1912 to 1916 contrasting the difference in the effect of the drought on groundwater levels at Chilgrove House with those at Dalton Holme.

2.2.4 Start date(s)

December 1913

The SGI gives a negative value for Dalton Holme, while the record for the same period gives a positive mean value at Chilgrove House (Bloomfield and Marchant, 2013). Absolute (a period of more than 14 consecutive days no one of which is a rain day) and partial droughts (a period of more than 28 consecutive days the mean rainfall of which does not exceed .01 in. per day) are reported from July 1913 (Mill *et al.* 1914).

2.2.5 End date(s)

November 1914

The SGI at Dalton Holme gives the end of the drought as December 1914 (Bloomfield and Marchant, 2013). Above average rainfall for November throughout the UK signalled the beginning of the end of the drought (Alexander & Jones, 2001). This was followed by rainfall in excess of the average by 107% in England during December (Mill & Salter, 1915).

2.2.6 Regional characteristics

The 1913-1914 drought was a highly localised event, limited to areas in the East of England. This is illustrated by a comparison of the negative SGI values at Dalton Holme and the positive values for Chilgrove House to the South for the same period (Bloomfield and Marchant, 2013). Due to the lack of a groundwater monitoring network in the early 19th century, there is a heavily reliance in this section of the report on rainfall statistics and written observations, with some inference (with the help of the SGI) on the state of groundwater resources. From an assessment of meteorological data, it appears as though the Dalton Holme observation borehole was ideally located to pick up the strongest signal of the drought. Surrounding meteorological observation stations to the North at Scarborough, West at Wetherby and South at Hull and Lincoln, all demonstrate that the drought signal was strongest in this region (Mill & Salter, 1915). The rainfall record at Hull only exceeds the average for 2 months in an 18 month record, while Sheffield 50 miles west and Market Overton 70 miles south exceed the average in 7 and 6 months respectively for the same time period (Mill & Salter, 1915). The well record at Therfield Rectory, Hertfordshire also shows a response to the drought, although not as strong as that at Dalton Holme, levels were still several meters below the average for 1914, suggesting the drought decreased in severity towards the south during the winter of 1913 (NGLA, 2015).

Relying on the SGI, rainfall and percolation data (Mill & Salter, 1913), it may be assumed that groundwater stocks would have been in at least reasonable health at the end of winter 1912, demonstrated by above average rainfall for most of the UK in the winter half year October 1912 - March 1913. However, the summer half year in 1913 experienced below average rainfall and rainfall in early winter 1913 missed Eastern parts of the country, with the principal dry area in the UK for 1913 lying between Whitby and Cromer (Mill *et al.* 1914). Dry conditions continued into January for areas in the East and South (Mill *et al.* 1914). Although there was rainfall during February and March with some Southern regions receiving in excess of twice the monthly average for March, Eastern areas received the lowest values compared to averages for that time of year (Mill *et al.* 1914).

Spring 1914 was exceptionally dry, particularly in the East, with Hull receiving less than 25% of the average for April (Mill & Salter, 1915). This pattern of below average rainfall continued throughout the summer, with some localised thunderstorms in June, July and August (Mill & Salter, 1915). Low levels in wells were observed in Hampshire, as well as Sussex and Brighton due to particularly arid conditions that prevailed in the region over the summer months (Mill & Salter, 1915). The low levels in these wells, as well as the SGI record at Chilgrove House (Bloomfield and Marchant, 2013) show an increasing drought signal for the South over this period and into October, the driest month in 1914 for the UK (Alexander & Jones, 2001).

2.2.7 Relationship with meteorological drivers

Parts of East Riding and Norfolk experienced partial drought for a period in excess of 60 days during 1913, caused by Easterly winds and a subsequent lack of depressions from summer to September, resulting in a lack of rainfall but average or close to average temperatures (Mill *et al.* 1914). Wind direction changed in early 1914 with south-westerly winds bringing a large number of depressions during February, however most of these affected northerly and westerly regions (Mill & Salter, 1915). The occurrence of notable thunderstorms during June and July was the result of an abnormal pressure system, with isobars running north to south (Mill & Salter, 1915). The intensity of these storms was enough to bring over half the July rainfall for Whitby in just 24 hours (Mill & Salter, 1915). Such large localised storms gave over 10% of yearly rainfall in just one day in certain areas (Mill & Salter, 1915), increasing the monthly average, but unhelpful for recharge. These thunderstorms also served to increase rainfall inequality between regions. There is a relatively large record in the literature of these thunderstorms and their effects, but relatively little on the impact of the drought.

The South of England experienced arid conditions during July, with temperatures at St. Pancras recorded at 34°C in the shade (BHS Chronology). Temperatures further North were closer to the seasonal average (Mill & Salter, 1915). Through November and December westerly winds brought frequent depressions to the UK, with Central England recording the highest monthly rainfall for any December for the region from 1873-2014 (Alexander & Jones, 2001). The severity of these year-end storms was such that rainfall averages for the whole of the UK were

7% above average, despite protracted meteorological droughts during the summer (Mill & Salter, 1915).

2.2.8 Relationship with surface water drought impacts

There is little mention of this drought period in the literature. This may be due to a focus on surface water impacts, a lack of groundwater monitoring at this time, or that the impacts of this drought were felt over a limited region. Of the few observations that were made, the state of surface waters offers some insight. Most of these impacts were felt during the dry end months of the drought, with low flows in brooks near Leicester from July to October (Richardson, 1931) and low water levels in Monkswood reservoir near Bath in October – a result of water stress due to low local spring yields (Mill & Salter, 1915).

2.2.9 Relationship with other environmental, agricultural, economic and social impacts

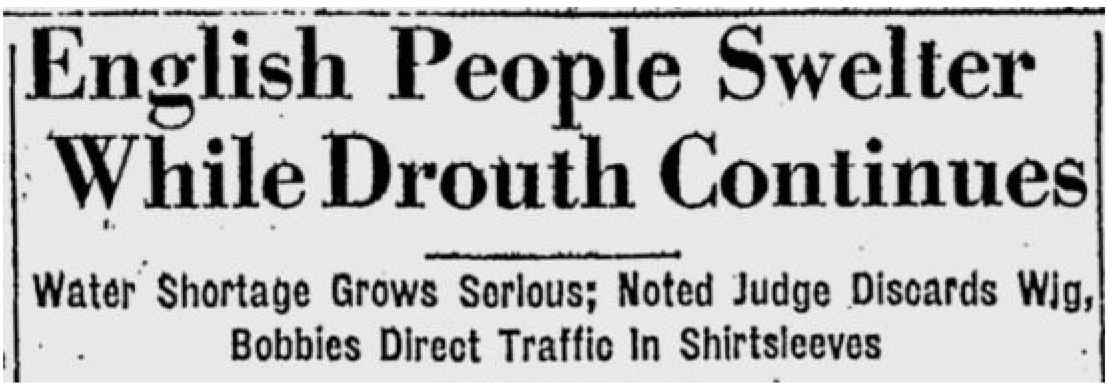
There were few agricultural issues associated with the entirety of the drought period, however there is some observation of the impacts of the aridity of the summer in 1914. These impacts were mainly felt in the counties of Surrey, Sussex, Hampshire and Buckinghamshire in the form of crop yields (BHS Chronology). Some areas experienced low yields due to the heat and low soil moisture, while some in some areas of Surrey, crops failed completely (BHS Chronology). There is no mention of any other impacts associated with this drought in the available literature.

2.2.10 Water resource management and legislative responses

Little information can be found on responses during or after the drought period. Although British Rainfall, 1914, (Mill & Salter, 1915) provides a comprehensive overview of the meteorology of the year, there is only limited, often anecdotal evidence of responses during the drought. These comments, mentioned in passing, only refer to the restriction of water supply due to decreasing local spring yields and the resulting increased strain on water resources at Monkswood reservoir (Mill & Salter, 1915). No evidence of legislation or change in water resource management practice has been found subsequent to this drought period. Whether this is a reflection of the impacts of the drought or the start of the First World War is unclear.

2.3 THE 1933 – 1935 DROUGHT

Autumn 1933 – autumn 1935



English People Swelter While Drouth Continues

Water Shortage Grows Serious; Noted Judge Discards Wig, Bobbies Direct Traffic In Shirtsleeves

Figure 6: Reporting of the 1933 Drought in a US newspaper.

2.3.1 Summary description

Investigation into the 1933-1935 drought has shown a lack of agricultural, social and economic records, as well as spatially variable hydrological and groundwater monitoring. The British Rainfall reports provide the majority of observations in this report. The 1933-1935 drought was defined by two consecutive dry summers, with a dry winter inbetween. The period from October

1932 to October 1934 is the third driest 24-month period on record. Anticyclonic weather patterns gave warm dry weather through 1933, affecting surface water in the South but particularly in the West. Groundwater was most severely affected in 1934 following the dry winter, with South and Southeast areas worst affected. The drought broke with spatially and temporally varied rainfall from autumn 1934 through 1935. The 1933-1935 drought is still used as a benchmark by several water companies to predict future drought impacts and reservoir storage needs. The Standardised Groundwater Index (SGI) ranks this period for Chilgrove House as the third most intense drought since records began.

2.3.2 Drought classification

Single-winter event, autumn groundwater start, summer meteorological start, South and Southeast focus with North West surface water impacts, SGI drought intensity of -1.36 for Chilgrove House, spatially and temporally varied end to the drought due to winter rainfall.

2.3.3 Graphical summary

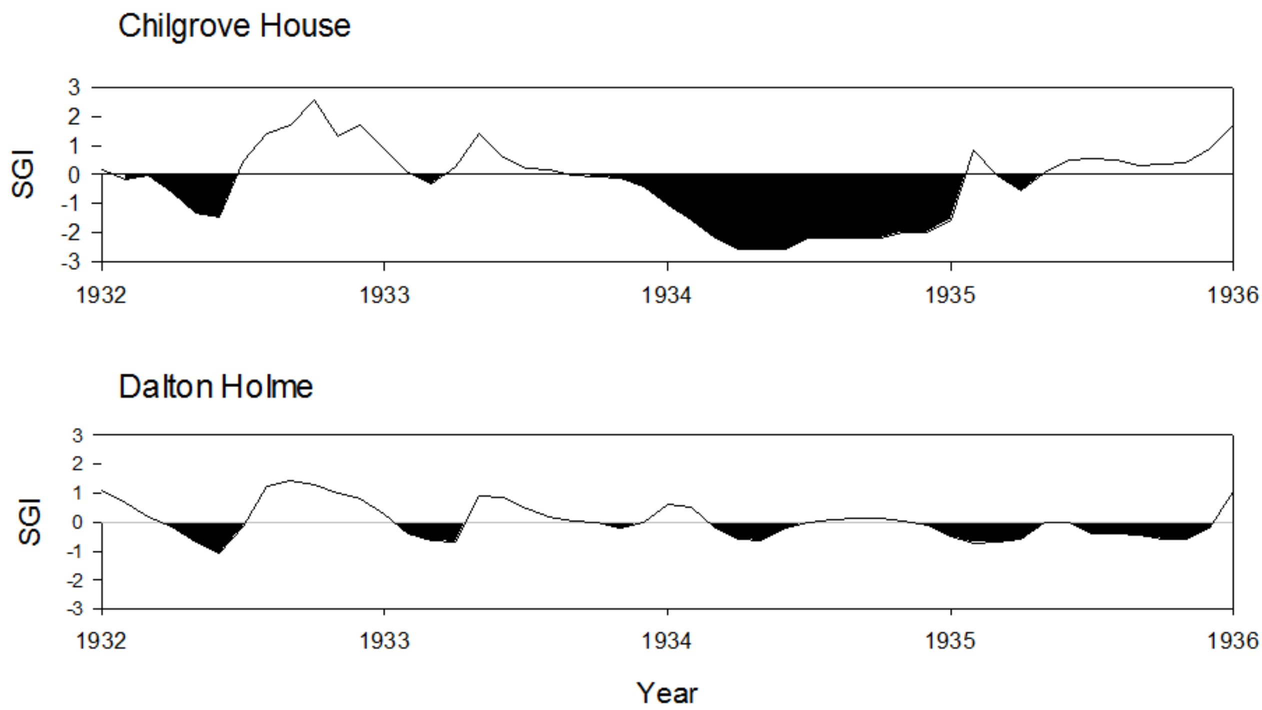


Figure 7: SGI time series from 1932 to 1936 contrasting the difference in the effect of the drought on groundwater levels at Chilgrove House with those at Dalton Holme.

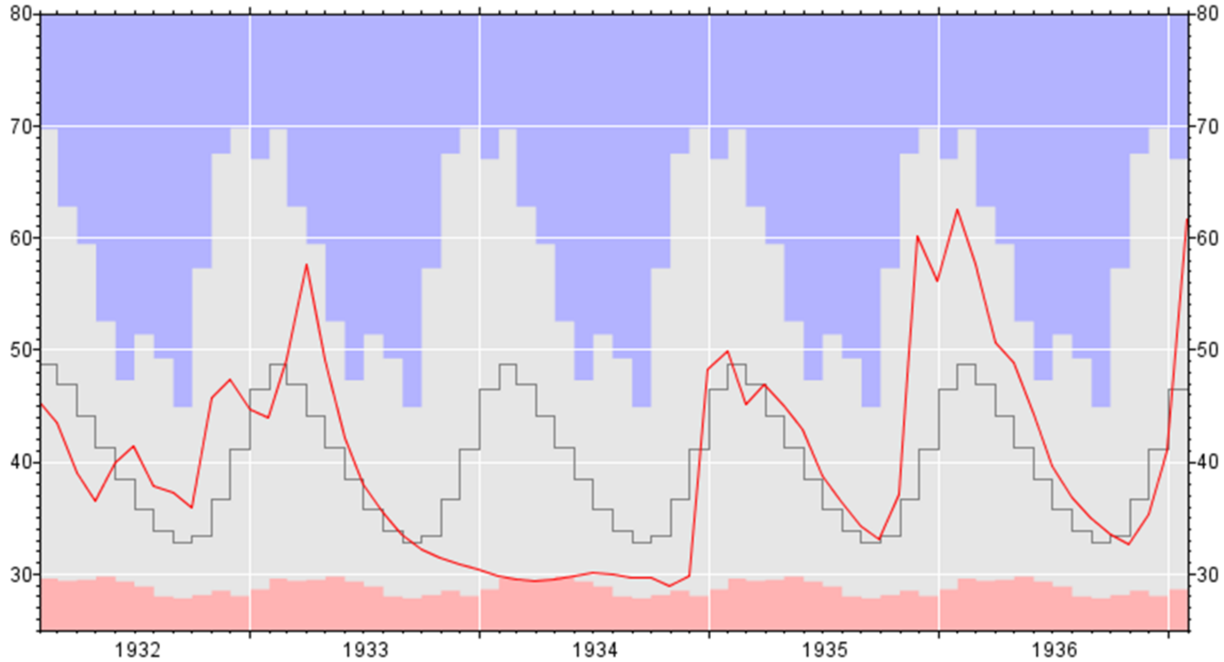


Figure 8: Compton: Groundwater Levels during the 1933 - 1935 drought

2.3.4 Start date(s)

September 1933

The SGI becomes negative at Chilgrove House in September 1933 (Bloomfield and Marchant, 2013), while the meteorological start date is given as autumn 1932 (Met Office, 1933).

2.3.5 End date(s)

April 1935

The end of the drought was spatially varied but the end date is given as the date when the SGI at Chilgrove House became positive (Bloomfield and Marchant, 2013), as this is the region where the drought impacts were greatest. The record at Dalton Holme becomes positive in November 1935 due to spatial rainfall patterns (Bloomfield and Marchant, 2013). The meteorological end date is given as autumn 1934 (Met Office, 1935).

2.3.6 Regional characteristics

Investigation into the drought period of 1933-1935 reveals a lack of data and information on the groundwater impacts of this period. The groundwater monitoring network was very limited, with just 5 operational wells, and there was limited reporting on the health of groundwater resources at the time, with academic discourse focussed mainly meteorological processes. In addition, there is less narrative and anecdotal evidence in the British Rainfall publications of this period compared to the 1913-1914 drought. Despite this, analysis of the data and limited literature of the period provides an overall picture of a dry summer 1933, followed by a dry and winter and another dry summer in 1934 (Met Office, 1934, 1935). The impact of this limited recharge during the winter of 1933/34 was most notable in the South and Southeast of England. There is almost a complete lack of recharge at Chilgrove House and Compton House near the South coast and Therfield Rectory just North of London during this period (NGLA, 2015). The well at Rockley near Marlborough shows very slight recharge over this period, and even higher recharge is seen at Dalton Holme, further north and east (NGLA, 2015). This recharge situation created serious groundwater resource issues during the summer and autumn of 1934, with the lowest groundwater levels at Compton House and Chilgrove House occurring during October and November respectively (NGLA, 2015).

2.3.7 Relationship with meteorological drivers

The period from October 1932 to October 1934 was the third driest 24-month consecutive period on record (Marsh *et al.* 2007). Winter 1932/33 had experienced sufficient rainfall for groundwater levels to be in a reasonably healthy state. However, the temporal and spatial variability of the rainfall meant that during 1993, the Northwest and Southwest and Wales had rainfall that was the lowest and 5th lowest on record respectively (Alexander & Jones, 2001). 1933 was the driest year since 1870, however the first half of the year experienced close to average rainfall. It was the dry summer, followed by the dry winter in 1933/34 that provided the onset of drought conditions. December 1933 was the driest month that year, and Central, Northwest and Southeast regions all experienced record rainfall lows from the 1873 – 2014 record (Alexander & Jones, 2001). This latter half of the year was warm and dry, caused by high pressure systems (Met Office, 1934). This high pressure remained in to 1934, bringing below average rainfall to the East in January and an incredibly dry February at just 26% of the average for the UK (Met Office, 1934). The lack of rainfall and above average temperatures meant there was little percolation to aquifers over the drought period (Thomson, 1947). Rainfall was particularly temporally and spatially variable towards the end of the drought period. The meteorological drought broke in autumn 1934, culminating in an exceptionally wet December, with areas on the South coast experiencing rainfall in excess of twice the monthly average (Met Office, 1935). This was followed by extremely variable rainfall in 1935, with the months of February, April, June and September exhibiting well above average rainfall, and the months of January, March, May, and July exhibiting well below average rainfall (Met Office, 1936). The widely varied rainfall led to a spatially varied end to the drought, with the SGI becoming a positive value in April 1935, while the SGI at Dalton Holme does not return to normal conditions until November 1935 (Bloomfield and Marchant, 2013).

2.3.8 Relationship with surface water drought impacts

Surface water was most severely affected in 1933, while groundwater experienced most impacts in 1934 (Marsh *et al.* 2007). There is anecdotal evidence that in late summer 1933 in Little Dewchurch on the Sandstone in Herefordshire, a spring flowed well while flow in the nearby river was poor (Richardson, 1935). This is perhaps testament to the incredibly dry latter half of 1933, while the first half was close to average (Met Office, 1934). The exceptionally low rainfall in the Northwest, Southwest and Wales gave surface water problems for these areas during 1933 (Met Office, 1934), with anecdotal evidence referring to low reservoir levels and low levels observed at Bewdley on the River Severn (Richardson, 1935). Low river levels were also experienced throughout the dry period of 1933 – 1934, with the Thames, Lee and Bedford Ouse all showing very low levels with a small period of recovery over winter 1933/34 (NRFA, 2015).

2.3.9 Relationship with other environmental, agricultural, economic and social impacts

There is very little information available on the impacts of the 1933-35 drought with relation to groundwater. British Pathé (1934) and Taylor *et al.* (2009) highlight the impacts on rural communities, with a reported £10 million required to prevent a water famine the following year.

2.3.10 Water resource management and legislative responses

There is almost no reference to water management measures taken during the drought, apart from appeals to the public to limit water use (Taylor *et al.* 2009). Despite this, there have been numerous subsequent actions taken in response to this drought period. Taylor *et al.* (2009) reports that many smaller local authorities struggled to exploit new resources, and there was a subsequent call for larger, catchment-area authorities. Several water companies, including Essex and Suffolk and Bristol use 1933/34 in future climate scenario impacts (Subak, 2000), while

Thames Water use the period to assess reservoir storage design (Thames Water, 2013). Downing (2004) highlights that the 1933-1934 drought demonstrated the need for a national water resource survey, an issue that had been discussed prior to this period. This led to groundwater being discussed more widely with policy makers in discourse about legislation, through the Inland Water Survey Committee set up in 1935 (Downing, 2004).

2.4 THE 1964 – 1965 DROUGHT

Autumn 1964 – late autumn/winter 1965

2.4.1 Summary description

The 1964-65 drought is widely underreported in the literature, despite the Standardised Drought Index (SGI) recording this period as the second most intense of the 19th Century at Dalton Holme. There is no mention of impacts on streamflow, despite evidence suggesting some regions experienced almost record lows in late 1964 and there are mentions in passing of 1964 being the second driest year since 1887. There is some reference however to groundwater levels with respect to rainfall, showing the main drought impacts were experienced in the Chalk, particularly in North and Eastern regions. The drought was caused by the very dry 1964/65 winter, with the exceptionally dry 1963/64 winter acting as a precursor. The underreporting of this drought period and its impacts may be an indication of the severity of the drought itself, the lack of visible impacts due to groundwater buffering, the short duration of the drought, the change in reporting style of the time, or the reorganisation of the hydrological and groundwater monitoring programmes from 1963 to 1965. Further investigation into this period from a hydrological perspective is required.

2.4.2 Drought classification

Single-winter event, an autumn groundwater start, an autumn meteorological start, affecting the Chalk in Northern and Eastern areas, SGI drought intensity of -1.30 at Dalton Holme, ending with heavy winter rainfall and dramatic increases in groundwater levels over the following year.

2.4.3 Graphical summary

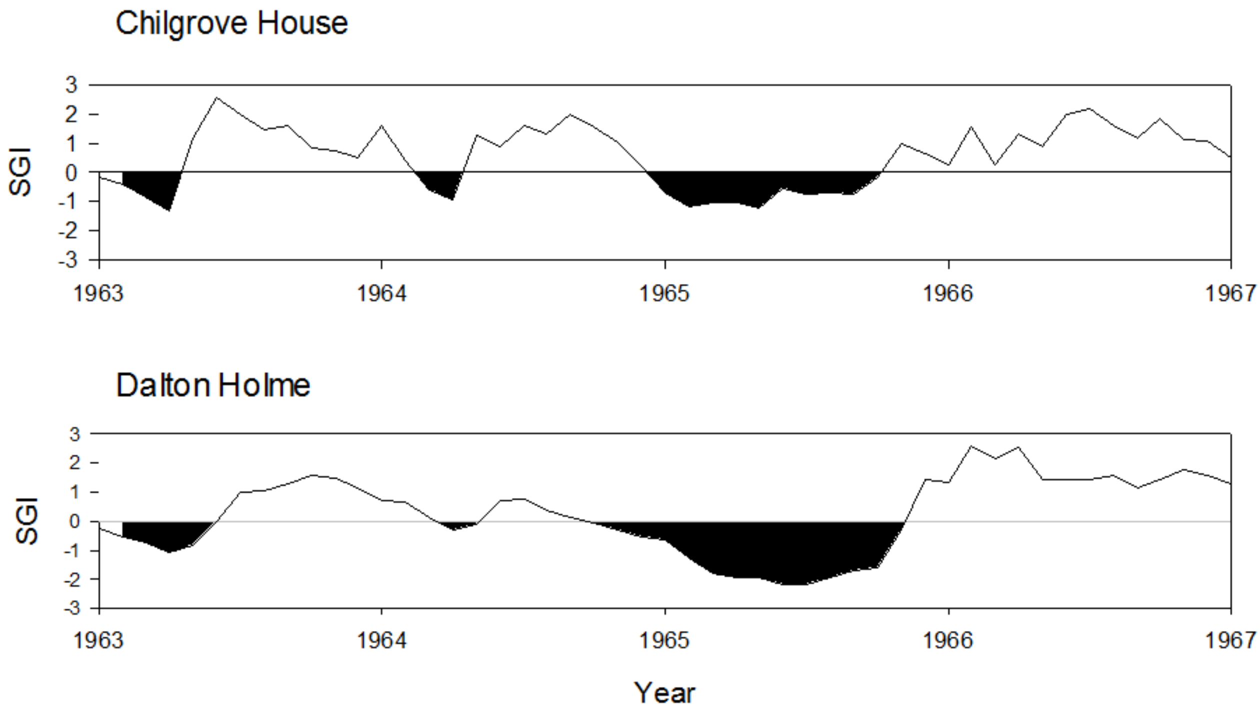


Figure 9: SGI time series from 1963 to 1967 contrasting the difference in the effect of the drought on groundwater levels at Chilgrove House with those at Dalton Holme.

2.4.4 Start date(s)

September 1964

The Standardised Groundwater Index becomes a negative value at Dalton Holme in September 1964 (Bloomfield and Marchant, 2013). This is in agreement with the meteorological drought start given by Phillips & McGregor (1998), although this date refers to the start of the core months of the drought.

2.4.5 End date(s)

October 1965

The Standardised Groundwater Index for both Dalton Holme and Chilgrove House returns to a positive value in October 1965 (Bloomfield and Marchant, 2013). Phillips & McGregor (1998) give the end date from a meteorological perspective as July 1965.

2.4.6 Regional characteristics

The groundwater drought 1964-1965 is not mentioned widely in the literature. There is no mention of the period in relation to major droughts of the 19th Century (Marsh *et al.* 2007), however the SGI ranks this drought as the second most intense at Dalton Holme over the same period (Bloomfield and Marchant, 2013). The drought mainly affected the Chalk and developed due to a dry summer from July onwards, with water tables falling from close to average levels (WRB, 1970). This development pattern was similar throughout the Chalk, but more pronounced at Dalton Holme, further north and east. A very dry winter 1964/65 meant there was a lack of recharge when it was most required and Dalton Holme reached near minimum recorded levels in the first half of 1965 (WRB, 1970). This dry winter prompted drought conditions in areas of the Chalk further south at the start of 1965. The drought intensity appear to be highly localised to Dalton Holme, however there is limited data from other northern regions during this period.

2.4.7 Relationship with meteorological drivers

The extremely dry 1963/64 winter acts a precursor to the 1964-1965 drought. The December 1963 – February 1964 rainfall is the lowest for these 3 months in a record that goes back to estimations in 1727 (WRB, 1970). Phillips & McGregor (1998) highlight two distinct meteorological drought periods, the first from January – April 1964 and the second from September 1964 - April 1965. These drought periods also coincided with more frequent easterly anticyclonic systems (Phillips & McGregor, 1998), associated with a negative NAO phase throughout the 1962-64 period (Parry *et al.* 2010). The first period of rainfall deficiency is observed in the literature (Cole & Marsh, 2006; Parry *et al.* 2010), however the second is only observed by Parry *et al.* (2010). There was subsequent rainfall from March to June that separated this dry winter from the start of the drought period (WRB, 1970) and created a negative SGI for a 2 month period in March and April at both Dalton Holme and Chilgrove House (Bloomfield and Marchant, 2013). 1964 was the third driest year since 1887 but attracted little attention (WRB, 1970) and is mainly mentioned in meteorological literature with reference to historical events (Phillips & McGregor, 1998; Marsh, 2004). The lack of autumn and winter rainfall and therefore recharge caused the drought, with soil moisture deficits occurring in all areas of Chalk outcrop from the end of May for the subsequent 15 months, indicating a lack of significant recharge over the period (WRB, 1970).

The intensity of the drought signal at Dalton Holme was due to the spatial variability of rainfall, with the Vale of York being relatively drier than England and Wales generally for January, June, July and May, with January being drier than anywhere in the British Isles (WRB, 1970). The drought ended with above average rainfall for September, a very dry October and a wet November and December, with heavy snowfall in parts (WRB, 1970). The Water Resources Board (1970) reports on the dramatic rise of groundwater levels in a number of boreholes from near minimum levels in the first quarter of 1965, to near maximum levels for the same time of year in 1966.

It is worth noting the change over time in the reporting style of the publication British Rainfall by the Met Office. The publications covering 1913-14 contained much more anecdotal evidence and described events associated with the meteorology, whereas publications of this period tend to be descriptive and refer only to rainfall.

2.4.8 Relationship with surface water drought impacts

There are few written hydrological reports given for this period that summarise the hydrological state of surface water. Parry *et al.* (2010) comment on streamflow deficiencies during the winter of 1964/65, with a Regional Deficiency Index (RDI; Stahl & Demuth, 2001) of 0.6 given for this period. Zaidman & Rees (2000) found streamflow was the fourth lowest year from 1960-95 for minimum flows. In addition, work by Jones *et al.* (2006) demonstrates there were low observed and modelled flows in the Wensum, Teifi and Dee. The lowest flow level at the River Wye was also recorded in 1964 (Jones *et al.* 2006). Parry *et al.* (2010) suggest that the limited impact of the drought was due to the buffering of streamflow by groundwater. There is perhaps a lack of recognition on local impacts of this buffering on groundwater levels, given the intensity of the drought at Dalton Holme.

2.4.9 Relationship with other environmental, agricultural, economic and social impacts

No report of impacts on the environment, agriculture, the economy or society from this period of drought has been found.

2.4.10 Water resource management and legislative responses

There is no report of water resource management used during this drought period, or indeed legislative responses post-drought. Parry *et al.* (2010) indicates the meteorological drought of 1962-64 caused the design and construction of many of the major reservoirs in the UK, however this is not observed elsewhere in the literature, with the growth of the UK economy and rising water demand cited as the reason for reservoir construction (Pearce, 1982). This drought period did however coincide with the Water Resources Act 1963, and the formation of the Rivers Authority and the Water Resources Board in October 1964 and its operational start in April 1965. Both the hydrological and groundwater reports are written retrospectively, published in 1968 and 1970 respectively. This may have been a factor in the lack of reporting of this dry period, or it may have been that the drought impacts were not severe enough to attract attention.

2.5 THE 1975 – 1976 DROUGHT

Spring 1975 - autumn 1976

“The 1976 Drought”

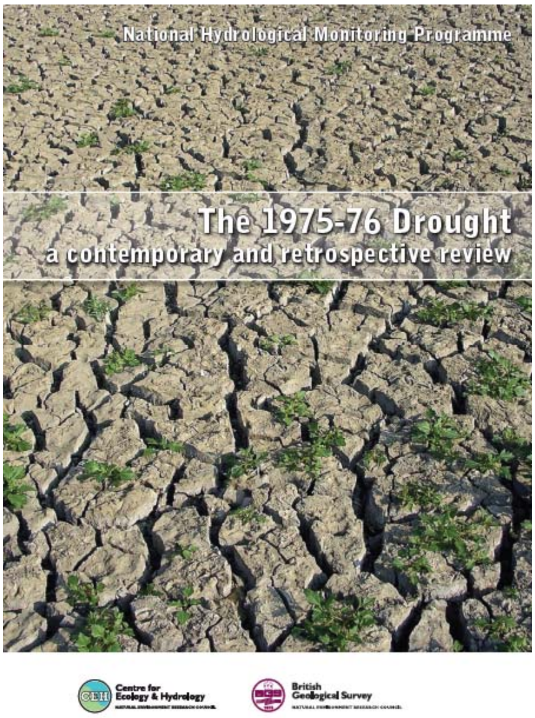


Figure 10: 1976 Drought Report.

2.5.1 Summary description

The 1976 drought was widely reported throughout the literature. The drought was caused by a lack of rainfall during the 1975/76 winter, a result of the Jet Stream taking a more northerly path. This was then propagated by an exceptionally arid summer, causing extreme soil moisture deficits. The majority of well minima were recorded during the drought period and the worst impacts were experienced in the South and East. There were also severe surface water impacts in the South West, Wales and Yorkshire. The drought had widespread and dramatic consequences for the environment, agriculture and infrastructure on a scale not witnessed before. The drought ended with the collapse of the blocking weather patterns, bringing unprecedented autumn rainfall. A record number of Drought Orders were implemented during the 1976 drought, as well as widespread hosepipe bans and the use of emerging flow augmentation schemes. The 1976 drought remains the primary benchmark for future drought planning.

2.5.2 Drought classification

Single-winter event, an autumn groundwater start, a spring meteorological start, affecting most of the UK but particularly south and east, SGI drought intensity of -1.81 at Chilgrove House, extreme summer aridity increasing in intensity towards the end of the drought period, ending with unprecedented autumn rainfall, with areas worst affected taking longer to recover.

2.5.3 Graphical summary

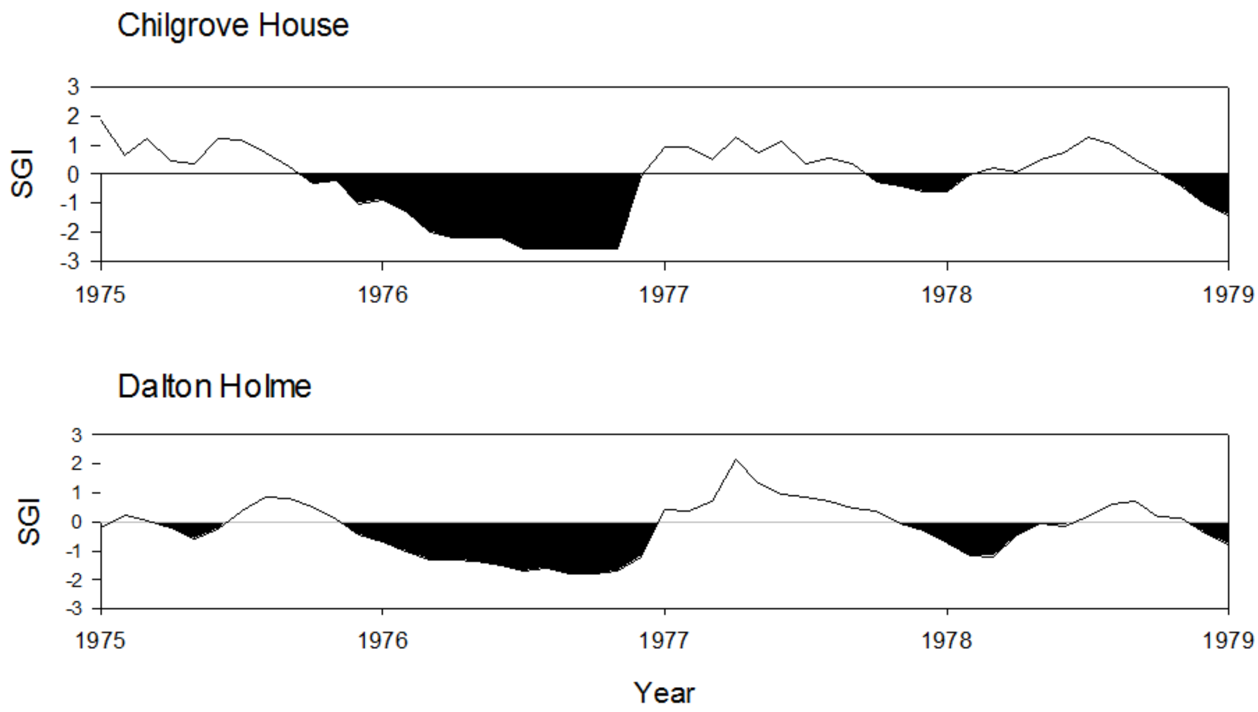


Figure 11: SGI time series from 1975 to 1979 contrasting the difference in the effect of the drought on groundwater levels at Chilgrove House with those at Dalton Holme.

2.5.4 Start date(s)

October 1975

The Standardized Groundwater Index (SGI) doesn't display a negative value until October 1975 for wells at Chilgrove House and Dalton Holme (Bloomfield and Marchant, 2013), however Day & Rodda (1978) state that water tables, particularly in the Chalk demonstrated below average levels for that time of year during September. May is given as the meteorological start date (Day & Rodda, 1978; Rodda & Marsh, 2011).

2.5.5 End date(s)

November 1976

The SGI for sites at Dalton Holme and Chilgrove House demonstrates the end of the drought in November 1976, while the SGI at Rockley shows a negative value until January 1977 (Bloomfield and Marchant, 2013). This is in agreement with Day & Rodda (1978). The official end of the drought is given in the literature as 6th October, with the removal of some localised restrictions, while the remainder of restrictions were gradually lifted through the latter part of October with the supply situation returning to normal (Rodda & Marsh, 2011).

2.5.6 Regional characteristics

In broad terms, the drought affected much of England, Wales and Eastern Scotland (Rodda & Marsh, 2011). The worst impacts on groundwater were across the South and East, where the most productive Chalk aquifers are found. The drought varied greatly in terms of both spatial and temporal distribution (Rodda & Marsh, 2011). The dryness of the 1975/76 winter was a key factor in the development of the drought. Estimated infiltration to the Chalk aquifers over this winter period in Lincolnshire, Norfolk, the Chilterns and Salisbury Plain and Dorset was 20% of the average for that time of year (CWPU, 1976). Other Chalk areas experienced below average infiltration but not to this extent. Areas of the Permo-Triassic Sandstones in Nottinghamshire and the West Midlands also recorded levels of infiltration below 20% of the average. Spring 1976 also exhibited low recharge rates, with many wells in the Southwest at record low levels for April (Day & Rodda, 1978).

The groundwater situation intensified alongside increasing aridity and decreasing rainfall, with a number of wells running dry during the months of June, July and August (Rodda & Marsh, 2011; Day & Marsh, 1978). Levels were particularly low at Chilgrove House, however similar extremes were not displayed further West (for example at Tetbury, Gloucestershire in the Great Oolite Series) (Day & Rodda, 1978). The Northwest and Northeast were significantly less affected, with White Water Pit Wood on the Permo-Triassic Sandstone near Blackpool exhibiting levels higher than those during the dry period in 1973 (NGLA, 2015). In some areas such as Bourne on the Lincolnshire Limestone, large falls in groundwater levels occurred, however these were largely due to public abstraction (Rodda & Marsh, 2011). Scotland was much less affected by the drought however Eastern Scotland's summer rainfall was the 2nd lowest on record for the area (Rodda & Marsh, 2011).

Inequities in the spatial distribution of the end of the drought also occurred. Some aquifers responded sooner than others and those in the Chalk took longer to respond. Some Chalk wells responded rapidly (e.g. Narborough, near Leicester) with recharge occurring in September but the well at Odsey in Norfolk took until January 1977 to rise from the summer minimum (Day & Rodda, 1978).

2.5.7 Relationship with meteorological drivers

For the period 1974-1975, above average rainfall meant aquifers were well stocked by spring 1975, with some experiencing recharge until early summer (Day & Rodda, 1978). However, winter rainfall was the lowest recorded since 1879/80 at 50% of the average for November-April (Rodda & Marsh, 2011). This low rainfall meant an 80% reduction in recharge and was reflected in low groundwater levels throughout the South and East (Rodda & Marsh, 2011). There continued to be below average rainfall with March to August 1976 experiencing just 52% of average (1916-1950) rainfall for that period (Rodda & Marsh, 2011).

The climax of the drought in terms of intensity occurred towards the end of the drought period between the months of June and August 1976. This is reflected in the exponential increase in the number of Drought Orders for England and Wales for this period. Eventually 140 drought orders were imposed, a total not since surpassed (Figure 12). Over the same period, most of England experienced mean daily maximum temperatures 3.0°C above average (Rodda & Marsh, 2011). By August, most of the UK had a soil moisture deficit of over 100mm (Rodda & Marsh, 2011), with some regions in the Midlands, South and East exceeding 138mm (Day & Rodda, 1978). The summer of 1976 is the most arid in the 244 year record (Rodda & Marsh, 2011). The drought ended in dramatic fashion, marked by record rainfall for the months of September and October 1976 (Alexander & Jones, 2001).

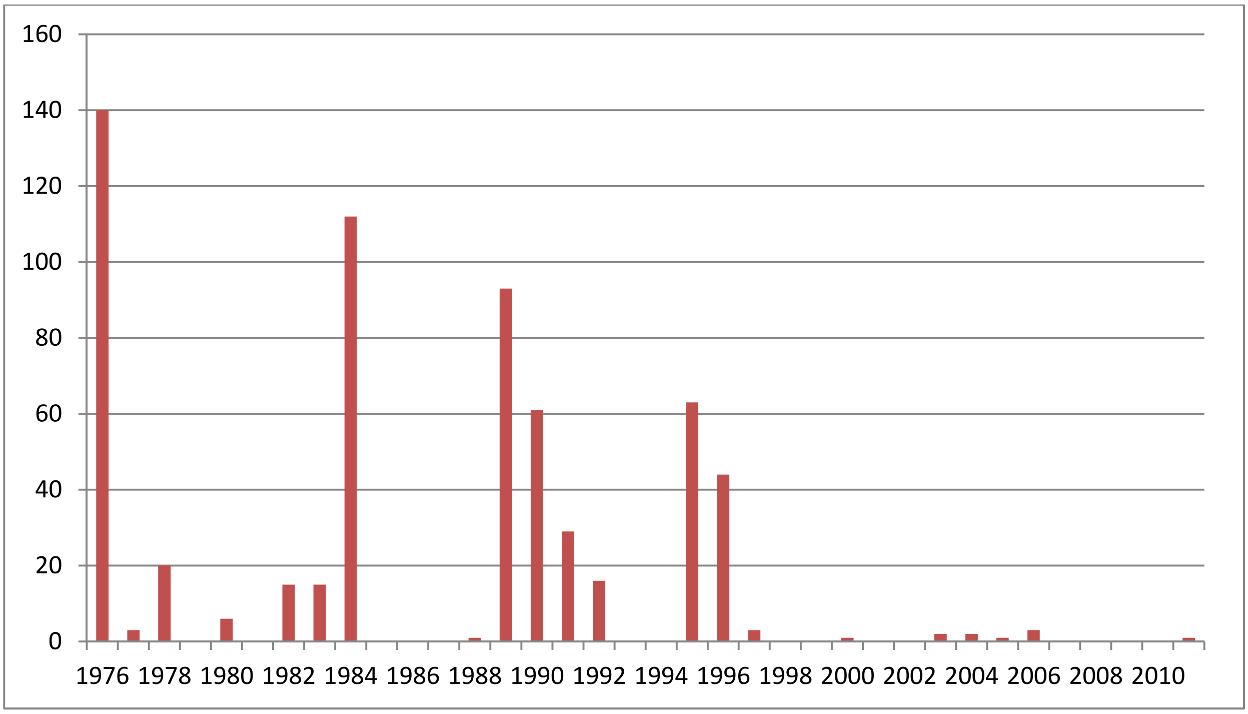


Figure 12: Numbers of drought orders per year, UK.

The literature points to a climatic forcing from the Atlantic as a reason for the anticyclonic and easterly weather types seen in the UK during the 1975-1976 drought (Rodda & Marsh, 2011; Fleig *et al.* 2011; Fowler & Kilsby, 2002a), brought on by a northerly movement of the Jet Stream (Ratcliffe, 1977b). The climax of the drought saw this Jet Stream move to an even more northerly position, while the formation of a southerly Jet Stream coincided with the break of the drought in September 1976 (Ratcliffe, 1977b; Rodda & Marsh, 2011).

2.5.8 Relationship with surface water drought impacts

Groundwater and surface water resource stresses were spatially very different for the 1975-1976 drought. The 1975-1976 drought had widespread impacts on surface water, mainly felt in South Wales, the Southwest and South Yorkshire. This contrasts with groundwater impacts in the South and East. The severity of the surface water drought was felt most heavily in Southeast Wales, where 1 million people had daily 17 hour cut offs in the water supply, whilst several Southwest reservoirs had between 20 and 50 days supply remaining (Rodda & Marsh, 2011). When compared with groundwater resources, reservoirs responded more rapidly to the decrease in rainfall, and recovered quicker as well. However, like groundwater, surface water also displayed huge disparity between regions. Farmoor reservoir near Oxford was at 68% capacity in June 1976, whilst some reservoirs in Gwent were at 14% and 22%, and Glamorgan reservoir was 70% full during August (Rodda & Marsh, 2011).

Areas of chalk aquifer that experienced low groundwater levels had impacts on the winterbournes and chalk streams, such as the receding of the perennial head of the River Kennet (Rodda & Marsh, 2011). This region experienced low groundwater, with the drying up of the Rockley borehole in nearby Marlborough (Day & Rodda, 1978) and a dramatic decrease in borehole yields at Newbury and Wantage (Rodda & Marsh, 2011). The Lambourn, a tributary to the Kennet, was augmented with pumped groundwater to aid the flow of the Thames during August 1976 (TWA, 1977; Wright & Berrie, 1987). A similar pumping scheme took place on the Candover Stream that feeds the River Itchen, with groundwater pumped into the river from hydrogeologically unconnected boreholes, augmenting summer low flows and abstraction near Southampton for public supply (SWA, 1976).

2.5.9 Relationship with other environmental, agricultural, economic and social impacts

A number of impacts have been documented for the 1975-76 drought, including the effects on agriculture, the environment, water quality and the cost implications for damage to built infrastructure. The following are some examples of documented impacts.

A short-term loss of vegetation was recorded, with particular effect on the Chalk grasslands (Hopkins, 1978). This had a profound impact on agriculture, with the greatest effect on dairy herds and a reduction in milk yield (Rodda & Marsh, 2011). The drying up of rivers and receding of winterbournes due to decreasing groundwater levels in the Chalk aquifers (Zaidman *et al.* 2002) had a massive impact on wild fish stocks in Southern England, with rod catches of salmon and migratory trout decreased by just over 75,000kgs and 27,000kgs respectively (Rodda & Marsh, 2011).

Longer-term environmental impacts included the impact on Beech tree populations. The species located on thin, freely draining soil overlying carboniferous limestone exhibit mortality of many mature trees, while those that did survive never recovered to pre-drought growth rates (Peterken & Mountford, 1996; Cavin *et al.* 2013). Some trees were still found to be dying 15 years on from the drought (Peterken & Mountford, 1996; Cavin *et al.* 2013).

Water quality impacts have been documented as a consequence of droughts with the mobilisation of nitrate at the end of a drought episode. However, the literature demonstrates that there was no significant increase in nitrate concentration in groundwater during or after the drought period (Rodda & Marsh, 2011; Day & Rodda, 1978). Only in exceptional circumstances were increases in nitrate concentrations found during the drought (some boreholes in East Kent) and despite decreases in stream water quality after the drought (Toms, 1977), groundwater quality for aquifers with a thick unsaturated zone maintained (Day & Rodda, 1978). Some reports of increased nitrate levels in boreholes were associated with particular intrinsic borehole characteristics and no long term consequences on groundwater have been found to be related to this period of drought (Day & Rodda, 1978).

The economic cost to the water authorities and water companies was relatively low (estimated at £34.3 million for the financial year 76/77 and £24.5 million for 77/78 (Gilliland, 1977)) when compared with the estimated cost of damage to properties due to subsidence in London alone was €800 million (EurAqua, 2004). 40,000 buildings, mainly located on the clays of London and the South East, were damaged, as well as roads and other structures (Rodda & Marsh, 2011).

2.5.10 Water resource management and legislative responses

Water restriction methods such as hosepipe bans, shut-offs, standpipes and numerous public campaigns were widespread throughout the drought period, particularly during the summer of 1976 (Rodda & Marsh, 2011; Pearce, 1982). The drought also saw the first formal Drought Act passed in August 1976, and the appointment of a Minister for Drought. The 1976 drought was the first to have a widespread public discourse (Cole & Marsh, 2006). In addition to these measures to control demand, supply was also managed. Pumping from groundwater boreholes into streams for subsequent public supply abstraction such as that at Candover (SWA, 1976), increased available water resources.

The literature appears to show a considerable change in attitudes towards water management post-drought, both from a consumer and supplier viewpoint. Pearce (1982) reports a change in some planning practices to include demand restriction return periods into water management planning, creating increased flexibility as a result of the realisation that consumers were obliging and able to reduce demand during periods of stress. This demonstrates an emergence of a new focus on consumers as partners in the control of demand (Taylor *et al.* 2009). Pearce (1982) also reports there was a shift in investment in infrastructure towards more linked systems rather than storage solutions, after the drought showed that integrated systems were more resilient. Other schemes such as the one at Candover (SWA, 1976) were also introduced to allow groundwater and local supplies to be used simultaneously (Cole & Marsh, 2006). However, Millar & Yates (2006) report that half of all English water regions built new reservoirs to increase storage capacity in response to the drought. The 1976 drought remains the primary benchmark for future drought planning (Rodda & Marsh, 2011). In addition, the Met Office dropped the terms "absolute" and "partial" drought after the 1976 event.

2.6 THE 1988 – 1993 DROUGHT

Summer 1988 – autumn 1993

"The 1988-1992 Drought"

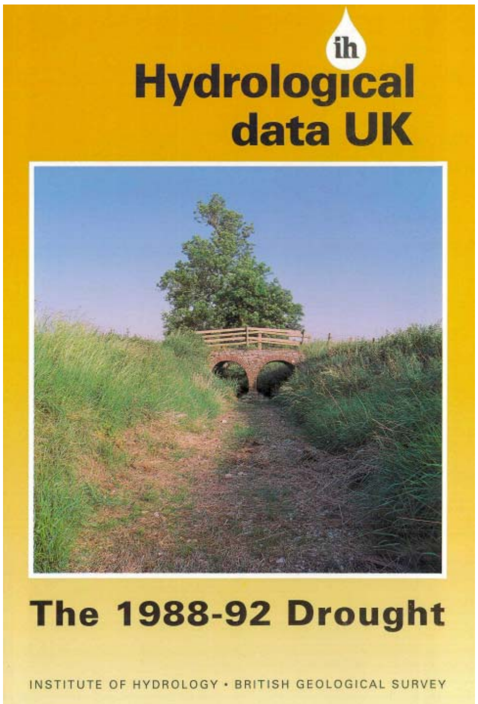


Figure 13: The 1988-92 Drought Report.

2.6.1 Summary description

The 1988-1993 drought was propagated by short winter recharge seasons, and the greatest impacts were felt in areas where groundwater is the principal source of water supply. It was a relatively long period of drought, particularly affecting the East Lowlands of England, due to the exaggeration of the Northwest/Southeast rainfall gradient. The highly spatial distribution of rainfall meant other areas experienced temporally varied drought impacts. The Chalk was the worst affected aquifer, with record lows observed in many areas. Impacts on the Permo-Triassic Sandstone were highly spatially variable and in some areas severe. The groundwater resources situation in the Chalk extended to the spring-fed stream network, which experienced unprecedented shrinkage, causing localised environmental problems. The end of the drought was also spatially dependant on the rainfall distribution, as well as being protracted in areas where groundwater abstractions amplified the drought effects.

2.6.2 Drought classification

Multi-winter event, a summer groundwater start, a spring meteorological start, focussed in the East, long event, short recharge seasons, SGI drought intensity of -1.53 for Dalton Holme, warm average temperatures for drought period, ending in summer/autumn rainfall, spatially distributed and in some cases protracted end to drought.

2.6.3 Graphical summary

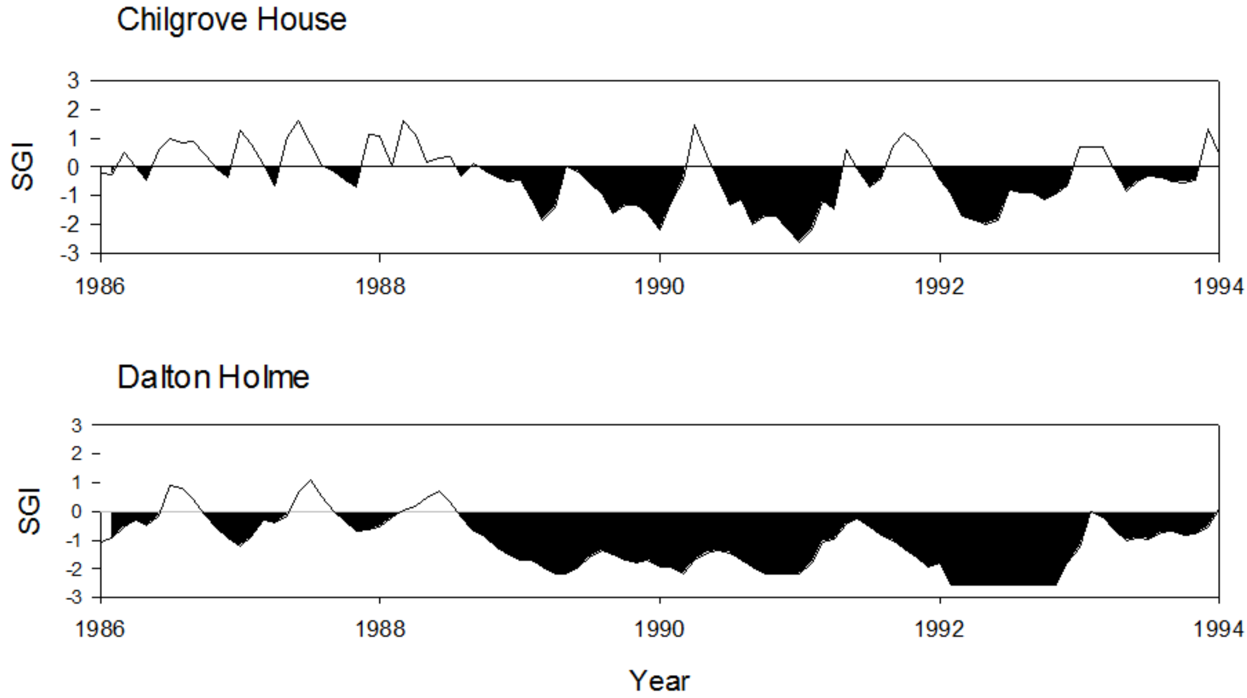


Figure 14: SGI time series from 1986 to 1994 contrasting the difference in the effect of the drought on groundwater levels at Chilgrove House with those at Dalton Holme.

2.6.4 Start date(s)

July 1988

The SGI becomes a negative value at Dalton Holme in July 1988 (Bloomfield and Marchant, 2013), whilst rainfall deficiencies define the start date as spring 1988 (Alexander & Jones, 2001).

2.6.5 End date(s)

November 1993

The SGI at Dalton Holme indicates an end to the drought in November 1993 (Bloomfield and Marchant, 2013). The large spatial variation in the breaking of the drought along with the protracted drought period itself gives varying end times for different regions. From a rainfall perspective, the drought ends in late summer 1992 (Alexander & Jones, 2001).

2.6.6 Regional characteristics

The 1988-1993 drought was particularly severe in terms of the impact on groundwater resources. It was most severe in regions where groundwater is the principal source of the water supply (Marsh *et al.* 1994). The drought was characterised by an exaggeration of the Northwest/Southeast rainfall gradient, with the Eastern Lowlands affected for the whole of the drought period and other areas experiencing variations in severity over time (Bryant *et al.* 1994; Marsh *et al.* 1994). Due to the length of this drought period, only certain aspects have been focussed on. A full report is given by Marsh *et al.* (1994). Drought severity was greatest in the North East during late 1989, before the impacts became more focussed on the Lowlands (Marsh *et al.* 1994). This was due in part to highly variable rainfall, giving huge spatial inequalities between regions outside the Lowlands (Bryant *et al.* 1994; Marsh *et al.* 1994). During winter 1990/1991, regions of the North and West Chalk experienced above average recharge, while less than half the average recharge occurred in the East Anglian Chalk (Marsh *et al.* 1994). The area from the Yorkshire Wolds to the East Chilterns experienced the lowest recharge this century over the drought period (Marsh *et al.* 1994). The Chalk was the worst affected aquifer, with summer 1992 yielding the lowest levels since 1900 (Marsh *et al.* 1994).

The drought was also characterised by very short winter recharge seasons (Bryant *et al.* 1994; Marsh *et al.* 1994). Although some of these recharge seasons (1989/1990) demonstrated rapid recharge and well recoveries, they also exhibited rapid recessions during the following summer (Marsh *et al.* 1994). These short recharge seasons meant levels in the Chalk were at record low levels at the start of summer recessions in both 1990 and 1992 (Marsh *et al.* 1994). Record low levels were also experienced in the majority of the other major aquifers by August 1992, and there was huge spatial variability in water levels in the Permo-Triassic Sandstone (Marsh *et al.* 1994).

There were also huge variations in groundwater recovery at the end of the drought. By the end of 1992, areas of the Chalk had returned to within the normal range, however in areas of Kent and in more Northerly outcrops of the Chalk, the recovery was much more varied (Marsh *et al.* 1994). A further dry period in 1993 between February and March meant careful monitoring of the groundwater resource situation was required (Marsh *et al.* 1994). The areas that took the longest to recover (into autumn 1993) were those areas that were worst affected by the drought and where groundwater abstraction had amplified the drought impacts (Marsh *et al.* 1994).

2.6.7 Relationship with meteorological drivers

November 1988 – February 1992 was the 4th driest and 2nd warmest 4 year period on record. The exaggeration of the prevailing rainfall gradient was initiated by a strong and long-lasting Azores High during winter 1988/89, pushing depressions carried by the jet stream on a more northerly path over Scotland and Scandinavia (Marsh *et al.* 1994). The 1989 recharge season was then delayed by a blocking anticyclonic system over Siberia (Marsh *et al.* 1994). Events such as these served to delay the recharge seasons, as well as alter rainfall patterns in the UK. Despite this overall pattern, rainfall was highly spatially variable within areas of Southern England over the drought period (Marsh *et al.* 1994). Evaporation was exceptionally high over this 4 year period due to above average temperatures (Marsh *et al.* 1994). This caused soil moisture deficits that caused further delay in recharge at the beginning of each winter (Marsh *et al.* 1994). A wet summer in 1992 signalled the end of the meteorological drought, raising soil moisture, allowing a wet September to contribute directly to recharge and arrest groundwater recessions in many areas (Marsh *et al.* 1994).

2.6.8 Relationship with surface water drought impacts

Shrinkage in the drainage network was an important element of this drought period, and was related to groundwater levels, particularly in the Chalk (Marsh *et al.* 1994; Peters *et al.* 2006). The magnitude of network shrinkage was unprecedented and much more extensive than in 1976 (Marsh *et al.* 1994). Many Chalk spring-fed streams experienced downstream migration of their perennial heads due to ever decreasing groundwater levels, as far north as the Yorkshire Wolds (Marsh *et al.* 1994). The problem of receding winterbournes was exacerbated by groundwater abstraction (Marsh *et al.* 1994). Decreased runoff in the East was highly related to the shrinkage of this stream network (Marsh *et al.* 1994). Reservoirs were also highly affected by the spatial variability of rainfall throughout the drought period (Marsh *et al.* 1994).

2.6.9 Relationship with other environmental, agricultural, economic and social impacts

Environmental issues associated with stream network shrinkage are widely reported in the literature. There was a considerable loss of habitat in the upper reaches of many streams (Marsh *et al.* 1994) and there was a profound short-term impact on Chalk ecosystems (Wood & Petts, 1999; Boulton, 2003). There were also issues regarding stream quality, with reports of inorganic phosphorous impacting on local biological communities in groundwater-fed streams (Boar *et al.* 1995) and nitrate production due to fluctuating water tables during the dry summer of 1989

(Reynolds & Edwards, 1995). There is little attention paid to agricultural impacts in the literature, suggesting this drought was not particularly severe for farmers and growers. There are also few reports of economic cost, aside from Lloyd-Hughes (2002) reporting that insured properties sustained £600 million worth of damage over the entire 4 years.

2.6.10 Water resource management and legislative responses

Several measures were implemented over the course of the drought period to limit demand and increase supply. Hosepipe bans started in summer 1989, followed by an appeal for restraint in demand by the water companies in May 1990 (Marsh *et al.* 1994). By the end of August, 18 million people were affected by restrictions (Marsh *et al.* 1994). The number of Drought Orders from 1989 – 1991, although not as high as the 1976 drought, was the highest for any 3 year period, and cumulatively was much higher than 1976 (see Figure 12 above). There were also measures to tackle supply issues, with leakage control, drilling exploratory boreholes and rejuvenating old ones (Marsh *et al.* 1994). There was also use of groundwater augmentation schemes (such as those on the Itchen and Little Ouse) and regional transfers between the Ely and Ouse (Marsh *et al.* 1994). The dry winter and autumn of 1988 also triggered the development of the National Hydrological Monitoring Programme in January 1989.

2.7 THE 1995 – 1998 DROUGHT

Summer 1995 - Winter 1997/98

“The 1995 drought”

“The 1995-1997 drought”

Figure 15: Barden reservoir, Yorkshire in 1995. ***Image by Steven Craven, geography.org/p91398***

2.7.1 Summary description

The 1995-1998 drought was caused by the exceptionally dry summer of 1995 and initially affected Yorkshire and the North West, particularly with respect to surface water. Impacts were severe and intensified by an unprecedented peak demand for water. From 1996-1998, the drought affected large regions of the UK and was propagated by a lack of winter recharge and a pattern of spatially distributed rainfall that, while allowing for improved soil moisture, prohibited large scale recharge. There was also a spatially varied end to the drought, with dry soils in some southern areas preventing recharge from occurring, and those areas worst affected taking longer to recover. The drought attracted widespread public interest and resulted in an assessment of the way water companies operated with respect to supply. It is worth noting the groundwater levels at Dalton Holme preceding this drought event, which indicate a very different pattern to general patterns observed throughout the UK, with just 9 non-drought months in a 115 month Standardised Groundwater Index (SGI) record, from the start of the 1988-1992 drought to the end of the 1995-1998 drought.

2.7.2 Drought classification

Multi-winter event, a summer groundwater start, a spring meteorological start, initially focussed in Yorkshire and North West but affecting southern areas as well, SGI drought intensity of -1.25 at Chilgrove, drought intensity varied spatially and temporally for different regions throughout period, ending with heavy winter rainfall, spatially distributed end to drought, with areas worst affected taking longer to recover, SMD geographically varied at termination.

2.7.3 Graphical summary

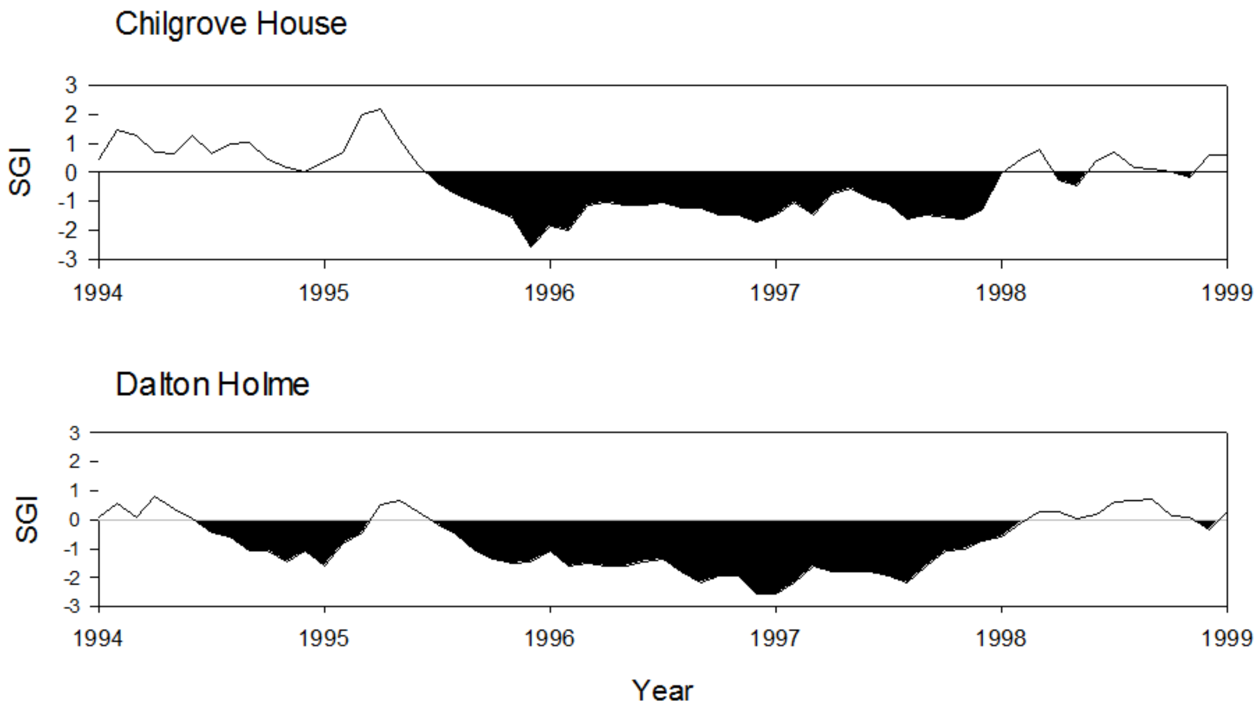


Figure 16: SGI time series from 1994 to 1999 contrasting the difference in the effect of the drought on groundwater levels at Chilgrove House with those at Dalton Holme.

2.7.4 Start date(s)

July 1995

The SGI becomes negative at Chilgrove House in July 1995 (Bloomfield and Marchant, 2013). The meteorological start is given as April 1995 (Marsh, 1995). The SGI record at Dalton Holme gives a different picture, however this is discussed in section 2.7.6.

2.7.5 End date(s)

January 1998

The end date as defined by the SGI is January 1998 at both Chilgrove House and Dalton Holme (Bloomfield and Marchant, 2013). Intensified rainfall in November 1997 gives this as the meteorological end date to the drought (Alexander & Jones, 2001). A varied response throughout the UK meant groundwater levels in some areas were still depressed in August 1998 (CEH, 1998).

2.7.6 Regional characteristics

When looking at the SGI for Dalton Holme, there is only a 6 month gap from the end of the 1988-1993 drought to a period of negative values from June 1994 to February 1995 (Bloomfield and Marchant, 2013). There is then a 3 month positive period before the onset of drought conditions again in June 1995. From an assessment of the literature (Marsh, 1995; CEH, 1995) it appears as though this is an exception to the general trend, with all aquifers being well stocked at the end of winter 1994/95. This period of drought at Dalton Holme from June 1994 to February 1995 is therefore a precursor to the main event but only for this particular geographic region. Yorkshire was particularly badly affected by the drought in 1995/96 and further investigation would be required to see if this precursory event accentuated drought impacts the following summer. Further localised impacts in Yorkshire were experienced in the summer of 1995 due to the spatial distribution of rainfall (Marsh, 1995). Impacts were also felt in the North West (the most severe drought on record for the region (Walker & Smithers, 1998)).

Apart from the South West, the drought was widespread during 1996, with areas of the Chalk in the east experiencing particularly low recharge over the 1995/96 winter (Marsh, 1995). The Permo-Triassic Sandstone also showed exceptionally low levels in North Wales and the Eden Valley, although areas to the North and West responded rapidly to rainfall in November 1996 and February 1997 (Marsh, 1995). This rainfall was highly spatially distributed, and Dalton Holme recorded a new minimum for November 1996 (Marsh, 1995). Groundwater levels began at close to the seasonal minima in summer 1997 with only 1979 and 1992 recording lower spring levels (Marsh, 1995). The end of the drought was also highly different across regions. Despite many boreholes back to average levels by the middle of January, the regions that were worst affected such as at Therfield and areas of the Permo-Triassic Sandstone, remained below average in August 1998 (Marsh, 1995; CEH 1998).

2.7.7 Relationship with meteorological drivers

The onset of the 1995-1998 drought period was caused by a northwards extension of the Azores High, bringing anticyclonic weather systems to the UK (Marsh, 1995), although one single pattern of atmospheric circulation did not dominate the drought (Parry *et al.* 2010). Spatially distributed rainfall created severe drought conditions for the North West and Yorkshire in 1995/96, while the end of the drought was characterised by widespread heavy rainfall throughout November and December 1997 – the most productive months for recharge in 3 years (Marsh, 1995). The distribution of soil moisture deficits over the drought period, both spatially and temporally, had huge impacts on the drought duration and recovery. A pattern of soil saturation, followed by below average rainfall in December 1996 and February 1997 meant recharge did not occur when the opportunity arose. In addition, the termination of the drought saw dry soils in areas of the Chalk in the Chilterns, the Lee basin and Cambridgeshire and Suffolk creating regionally depressed groundwater levels (Marsh, 1995).

2.7.8 Relationship with surface water drought impacts

Surface water impacts were widespread throughout the drought period. The greatest impacts were felt in Northern areas in 1995, with reservoirs in Yorkshire at between 20% and 15% of capacity towards the end of 1995 (Marsh, 1995; Fowler & Kilsby, 2002a) and some failing completely (Bakker, 2000). Low river flows were widespread, however not as severe as 1976 or 1984 (Jones & Lister, 1998). Some surface water impacts were felt during later periods of the drought, with the full extent of the stream network shrinkage not occurring until summer 1997 (CEH, 1997).

2.7.9 Relationship with other environmental, agricultural, economic and social impacts

There were severe and wide-ranging impacts to the environment during the 1995-1998 drought. These were amplified by unprecedented peak demand for water (Marsh & Turton, 1996; Walker & Smithers, 1998). As in previous drought periods, shrinkage of the stream network (CEH, 1997) caused the loss of habitats and impacted macrophyte populations (Westwood *et al.* 2006). Increased levels of nitrate (Morecroft *et al.* 2000) and sulphur (Evans & Monteith, 2001) were found during the termination of the drought, while algal blooms threatened water supplies (Ferguson *et al.* 1996) and caused problems with recreational water use (Everard, 1996). Despite these issues and the disruption of fisheries (Everard, 1996), there were increases in insect abundance, particularly in the South due to increased temperatures during the summer of 1995 (Morecroft *et al.* 2002). Many of these acute issues were caused by high temperatures in the summer of 1995; however issues surrounding the long term depletion of water resources, such as the build-up and subsequent flushing of nutrients and the loss of the headwater stream network, were due to the longevity of the drought period.

2.7.10 Water resource management and legislative responses

The 1995-1998 drought was highly politicised due to the nature of its impacts. It was argued that the shortfall of service caused the intensification of drought severity as it transpired that supply leakage was highest in the worst affected areas of Yorkshire and the North West (Taylor *et al.* 2009). This caused public outcry (Marsh & Turton, 1996) and calls for regulation of company performance (Taylor *et al.* 2009). Parliamentary papers were published on controlling leakage, and Taylor *et al.* (2009) report that mandatory leakage targets were set by Ofwat. Yorkshire Water was held accountable for rota cuts and in response, invested £50 million in a water transfer scheme from the River Tees to the River Ouse (Taylor *et al.* 2009). Other areas also installed new schemes, with the Suffolk Hartismere Resource Zone providing two new groundwater sources and improved infrastructure for transfer (Lunn *et al.* 2013). Northumbrian Water have used the 1995-1996 period as a marker for drought demand planning (Gray & Lunn, 2013). As well as the schemes implemented after the drought, several water companies enforced hosepipe bans during the drought (Marsh, 1995) and there were 97 drought orders over the 1995-1996 period (Defra, 2012). Yorkshire Water moved water by tanker during the 1995 summer as a result of supply issues (Fowler & Kilsby, 2002a).

2.8 THE 2003 – 2006 DROUGHT

Spring 2003 – winter 2006/2007

"The drought of 2003"

"The 2004-2006 drought"

Figure 17: Parched field near Bury St Edmunds, 2006. ***Image by Bob Jones, geography.org/p020356***

2.8.1 Summary description

The 2003-2006 drought was propagated by a lack of sufficient winter rainfall, and the majority of impacts were felt in areas where groundwater is the principal component in the water supply. The drought is reported as two separate meteorological and hydrological events in the literature, however an assessment of the Standardised Groundwater Index (SGI) and groundwater data demonstrate that these two episodes are highly linked. The 2003 drought had implications for most of the UK and rain that fell in the winter of 2003/04 only served to localise areas of groundwater drought to the Southeast. The drought was highly localised within the South of England, with many areas of the Chalk exhibiting different levels of water stress. Subsequent persistent anticyclonic conditions resulted in an exaggeration of the Northwest/Southeast rainfall gradient and sustained this localisation from spring 2004 until the drought intensified in 2006 with the hottest July for the UK since records began. The drought ended with cyclonic conditions in October 2006 that brought recovery for most groundwater levels in January 2007, although recovery was highly spatially variable. The drought also caused migratory fish deaths due to the drying up of winterbournes on the Chalk however these were not as severe as those in previous drought periods.

2.8.2 Drought classification

Multi-winter event, a spring groundwater start, a winter/spring meteorological start, initially affecting much of UK, later focussed in the Southeast but highly spatially varied within region, SGI drought intensity of -1.14 at Chilgrove House, increasing in intensity towards the end of the drought period, ending with unprecedented winter rainfall and rapid increases in recharge rates, spatially distributed end to drought, with areas worst affected taking longer to recover.

2.8.3 Graphical summary

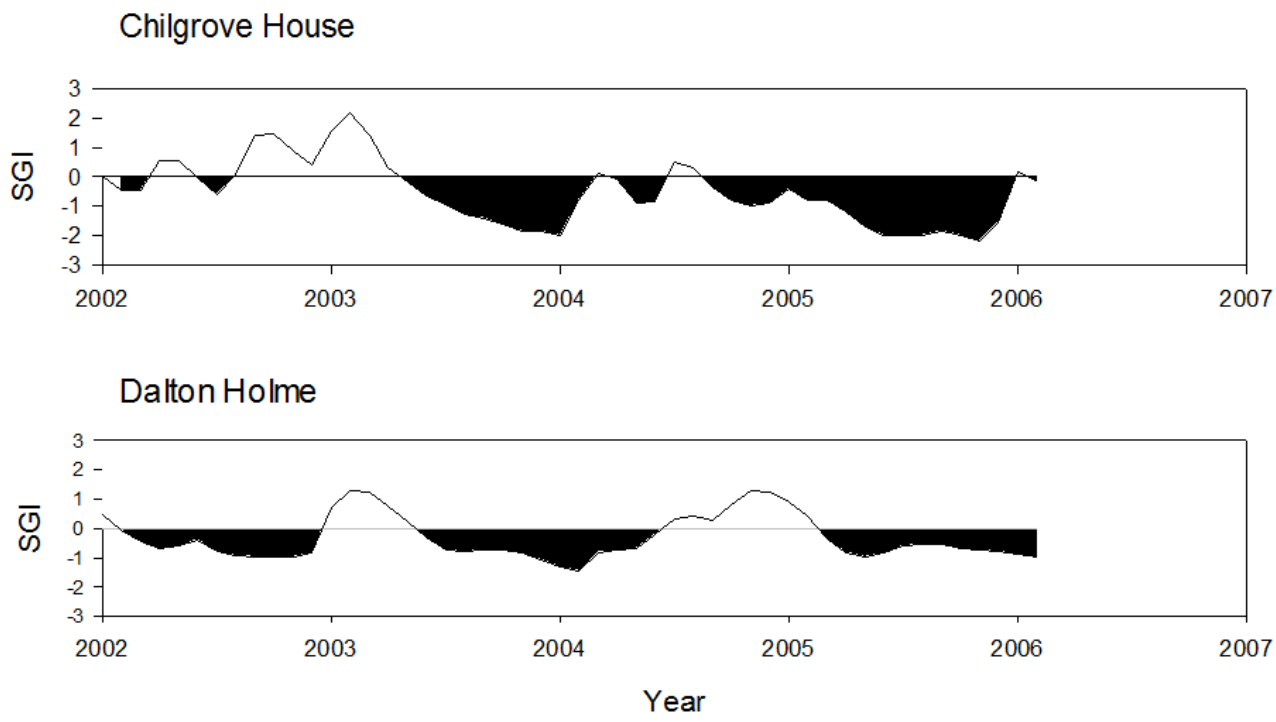


Figure 18: SGI time series from 2002 to 2007 contrasting the difference in the effect of the drought on groundwater levels at Chilgrove House with those at Dalton Holme. Note SGI record ends in early 2006.

The spatial variability of the drought period can be seen in Fig. 8. The drought is clearly less severe in the North at Dalton Holme, and also has a large break within the two periods of drought highlighted by Marsh (2004; 2007). The drought at Chilgrove House is more continuous, highlighting the impact on the drought on groundwater resources in the Southeast.

2.8.4 Start date(s)

May 2003

The Standardized Groundwater Index becomes a negative value in May 2003 (Bloomfield and Marchant, 2013). For Chilgrove House, this value becomes positive for July and August 2004 but remains negative until the drought ends. From a groundwater level perspective, it isn't until July 2003 that groundwater levels are reported as being below the average for areas of the Limestone and southern areas of the Chalk (CEH, 2003). This is again in contrast with the rainfall and runoff perspective, where late winter / early spring 2003 is given as the start date (Marsh, 2004).

2.8.5 End date(s)

December 2006 / January 2007

Although soil moisture deficits were eliminated during November and December, it was not until late December, early January that water-tables began to show significant increases in the responsive aquifers (CEH, 2007). The slower to respond and worst affected areas of Chalk and Permo-Triassic Sandstone took until March to return to seasonal averages (CEH, 2007). Late October 2006 is regarded as the turning point for the drought in terms of rainfall and runoff (Marsh, 2007), with momentum gathering through November (CEH, 2006).

2.8.6 Regional characteristics

The 2003-2006 drought caused an exaggeration of the Northwest/Southeast rainfall gradient, meaning the groundwater drought period was confined mainly to Southern Britain, with the English Lowlands being particularly affected (Marsh, 2004; CEH, 2004; Marsh, 2007). There was a highly spatial signal to the 2003-2006 drought, with the Southern Chalk, notably in the Chilterns, substantially worse off than outcrops further North (Marsh, 2007), as demonstrated in a comparison of the SGI between Chilgrove House and Dalton Holme. The responsive Chalk was the worst affected in the Chilterns, along with some areas of the Jurassic Limestone in the Cotswolds (Marsh, 2004). While the drought was extremely severe in places, the limited spatial extent meant that from a water resource perspective, it was not as serious as droughts of the early and mid-1990’s (Marsh, 2007).

Groundwater levels throughout the UK were particularly well stocked at the start of 2003 however the dry months of February to May depleted levels on a very spatially variable basis, with areas of Chalk being particularly vulnerable (Marsh, 2004). Levels continued to decline through late summer and autumn with the driest February-October since 1921 and high soil moisture deficits (Marsh, 2004). The soil moisture situation was ameliorated slightly in December and January and there was the opportunity for recharge to occur in February 2004 (CEH, 2004). Some recharge did occur but this was highly localised and so for many boreholes, groundwater levels were at their lowest spring peak for 7 years (Marsh, 2007). The subsequent 2004-2005 and 2005-2006 winters were particularly dry, and apart from a period of rainfall in April and May 2004 (subsequently causing the SGI at Chilgrove House to become positive for July and August), there was a steady decline in groundwater levels throughout the Southeast of England until the drought ended (Marsh, 2007). In general, soil moisture deficits declined rapidly through October 2006, restoring runoff and recharge rates throughout the English Lowlands (Marsh, 2007). Those regions of aquifer that were worst affected by the drought took much longer to recover, yielding a spatially variable end to the drought (Marsh, 2007).

2.8.7 Relationship with meteorological drivers

From a meteorological perspective, the literature (Marsh, 2004; Marsh *et al.* 2007, Marsh, 2007) highlights two distinct periods of drought, one from February to May 2003, and one from late autumn 2004 to winter 2006, whilst highlighting the 2003 episode as a precursor to the latter episode. However, from a groundwater perspective, the drought begins in 2003, becomes more localised in winter 2003-2004 and then gradually worsens until winter 2006. The rainfall that demarcates the two episodes caused recharge in some areas (Northern and Western) but only served to decrease an elevated soil moisture deficit in others throughout December and January (CEH, 2003; CEH, 2004). As a result, there was the prospect of recharge through late winter 2004 but this never materialised. This helped exaggerate localised drought conditions in the Chilterns and Cotswolds which remained throughout the drought period (Marsh, 2007). The start date of the 2004-2006 drought as given by Marsh (2007) and the start date as defined by the SGI series at Chilgrove House in 2004 are very close, suggesting groundwater resources were very stressed, and not much rainfall deficiency was required for the SGI to return to a negative value after a two month deviation from groundwater drought conditions.

Although rainfall for much of Southeast was close to average for May to October in 2005 and 2006, winter rainfall was significantly below average, creating a steady decline in groundwater levels throughout the entire drought period (Marsh, 2007). Conditions improved slightly with a damp late spring in 2006, but the hottest July for most of the UK since records began in 1914, meant the drought intensified towards its end (Marsh, 2007; Prior & Beswick, 2007). Both the

2003 and 2004-2006 periods were caused by the persistence of anticyclonic conditions over the UK in 2003 (Fink *et al.* 2004) and Southern Britain in 2004 (Marsh *et al.* 2007). The regional location of this weather type in 2004 forced low pressure systems over Scotland and amplified the Northwest-Southeast rainfall gradient (Marsh *et al.* 2007). Convective storms in the late summer of 2006 improved some local soil moisture deficits but in some areas such as Cornwall, rainfall deficiencies increased (Marsh, 2007). It wasn't until October that soil moisture deficits improved enough to allow for rainfall and runoff in the English Lowlands (Marsh, 2007). A pattern of frontal systems meant October 2006 to May 2007 was the wettest on record for the UK (Marsh, 2007).

2.8.8 Relationship with surface water drought impacts

As explained in the above section, there is disagreement between groundwater and meteorological patterns through the latter part of 2003. This is also the case when comparing groundwater to surface water. Rainfall in the late autumn of 2003 allowed river flow to increase and by December, the reservoirs of England and Wales recorded their largest single month rise, although this same pattern was much more attenuated further north (Marsh, 2004). The speed of recovery in reservoirs and rivers signalled the end of the 2003 drought for surface water however the slower response time of groundwater, meant the same patterns were not seen in some aquifers, such as the Permo-Triassic sandstone (Marsh, 2004; Marsh, 2007).

Marsh (2004; 2007) provides a detailed analysis of the spatial distribution of surface water impacts throughout the period 2003-2006, with Marsh (2007) highlighting the impact of groundwater connection to rivers in relation to runoff. River flows in spring fed, permeable catchments were more heavily affected than more responsive rivers, where short lived spates helped maintain runoff (Marsh, 2007). These spring fed rivers also took longer to recover (CEH, 2006). As a result, the groundwater and surface water impacts of the drought were felt in similar areas, with the exception of Cornwall and other areas of the Southwest where groundwater is not extensively monitored.

2.8.9 Relationship with other environmental, agricultural, economic and social impacts

There is evidence of migratory fish deaths (Marsh 2007; Marsh *et al.* 2007; EA, 2012) due to the drying up of headwaters as a result of lowering groundwater levels (Marsh *et al.* 2007; Marsh, 2007). The drought also created problems with low oxygen levels in surface water (Marsh, 2007) and subsequent blue-green algal blooms, reduced breeding areas of wading birds (EA, 2012) and oak and beech mortality (Green & Ray, 2009). There was also heat damage to roads during summer 2006 with an associated estimated cost of £3.6million in Oxfordshire alone (Prior & Beswick, 2007). There were however benefits to farmers and tourism due to improved meteorological conditions (Prior & Beswick, 2007).

The presence of literature appearing after the 2006 drought indicates that the episode had a relatively large social impact, and there was an extensive academic engagement in public thinking (Medd & Chappells, 2007; Medd & Chappells, 2008; Taylor & Trentmann, 2008; Taylor *et al.* 2009; Dessai & Sims, 2010). There was public disillusionment and criticism of the operations of water companies (London Assembly Committee, 2006; Dessai & Sims, 2010), particularly with respect to supply leakage and some were subsequently reluctant to operate demand management (Taylor *et al.* 2009; Taylor & Trentmann, 2008).

2.8.10 Water resource management and legislative responses

Hosepipe bans affected around 15.6 million people in England during the summer of 2006 (EA, 2012) while water restrictions affected 13 million across southern England (Marsh *et al.* 2007). There were also localised public campaigns (London Assembly Committee, 2006; Taylor & Trentmann, 2008). It has been reported that water companies supply systems fared better than previous drought periods due to better supply systems and as a result, water resource impacts have been attenuated (EA, 2012).

Leakages were a major source of both public indignation and supply problems (Ofwat, 2006; Taylor *et al.* 2009) causing investment to mainly be directed at improving supply issues both during (London Assembly Committee, 2006) and after (von Christierson *et al.* 2011) the drought. The growing concern expressed in the literature regarding public participation in drought demand management (Taylor *et al.* 2009; Dessai & Sims, 2010) was reflected in the decision by the Government to announce reform of hosepipe bans and non-essential use restrictions (Taylor & Trentmann, 2008).

2.9 THE 2010 – 2012 DROUGHT

Winter 2010/11 – summer 2012

"The 2010-12 drought"

Figure 19: A dry river bed in Hampshire, 2012. Image ©BGS, NERC 2012.

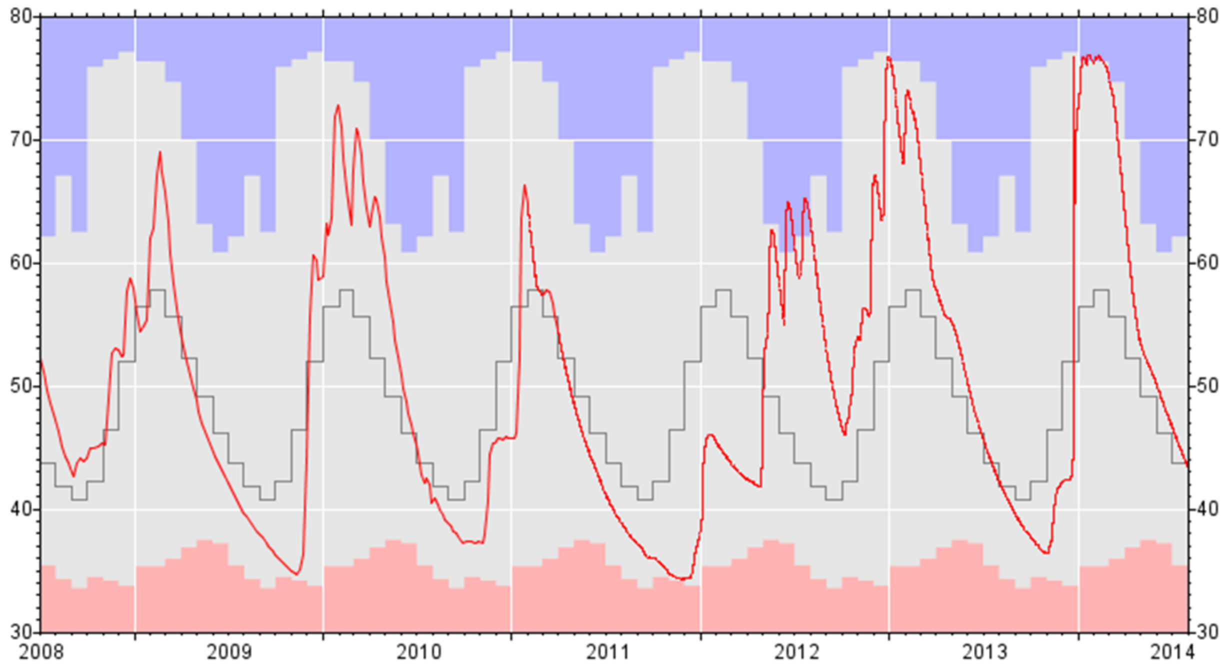
2.9.1 Summary description

The 2010-2012 drought was caused by blocking high pressure, causing the Jet Stream to move to a more northerly position. The drought was temporally and spatially variable, affecting North West regions initially, before evolving to an exaggeration of the Northwest/Southeast rainfall gradient. Drought conditions were propagated by a lack of winter rainfall in consecutive years, despite close to average summer rainfall. The Chalk was the worst affected aquifer throughout the entire drought period, and surface water impacts due to the contraction of the stream network were the most severe in the last 50 years. Further impacts on water quality and the disruption to farming due to low soil moisture were also reported. A large number of drought mitigation schemes were at the disposal of the authorities including low flow augmentation, the exploitation of emergency groundwater sources, hosepipe bans and Drought Orders. The termination of the drought was dramatic, caused by the southerly movement of the Jet Stream bringing the wettest April to the UK in at least 230 years. Marsh *et al.* (2013) provide a comprehensive overview of the drought period from all hydrological perspectives, on which this report is largely based.

2.9.2 Drought classification

Multi-winter event, a winter groundwater start, a winter meteorological start, focussed initially in the North West before becoming focussed in the South East, increasing in intensity towards the end of the drought period, ending with unprecedented spring rainfall and rapid increases in recharge rates, spatially distributed end to drought, slowest-responding aquifers taking longer to recover.

2.9.3 Graphical summary



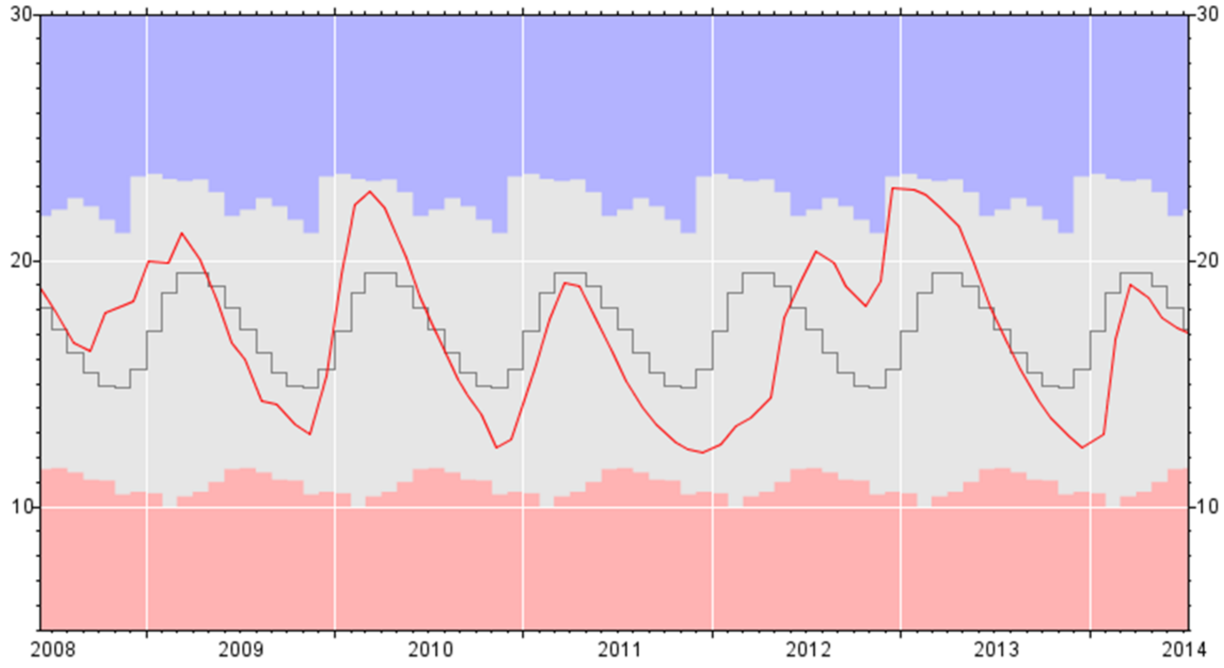


Figure 20: Chilgrove House and Dalton Holme groundwater level hydrographs for the 2010s showing suppressed groundwater levels during the 2011-12 drought.

2.9.4 Start date(s)

December 2010

In general, groundwater levels were below average in the majority of aquifer outcrops by December 2010 (Marsh *et al.* 2013). The meteorological drought started much earlier in December 2009/January 2010, but did not impact groundwater until later due to the spatial distribution of subsequent rainfall (Marsh *et al.* 2013).

2.9.5 End date(s)

June 2012

Levels in index wells throughout the Limestone and southern and western Chalk outcrops were seasonally above average by June 2012 (Marsh *et al.* 2013). April is regarded as the meteorological end date (Marsh & Parry, 2012).

2.9.6 Regional characteristics

The 2010-12 drought began in North West England in December 2009. The situation moderated throughout 2010 but by 2011, an extreme exaggeration of the Northwest/Southeast rainfall gradient had been established (Marsh *et al.* 2013). Groundwater levels were generally within the normal range during the first half of 2010 but a very weak autumn recovery and subsequent frozen ground meant levels were below the seasonal average at the years end in all but the most responsive northern aquifers (Marsh *et al.* 2013). The groundwater recovery through 2010/11 was spatially variable and lead to very depressed groundwater levels throughout the UK, albeit higher than the minima experienced in the mid-1990s and early 2000s (Marsh *et al.* 2013). The delayed onset of the 2011/12 recharge season meant that by late 2011 private and observation boreholes were failing in areas such as Wiltshire and Shropshire (Marsh *et al.* 2013). Recharge for the winter half year 2011/12 was below 20% of the seasonal average over wide areas, and many well hydrographs show no sign of winter replenishment (Marsh *et al.* 2013). Most boreholes reported new March minima for 2012 and only in 1992 has overall aquifer storage been lower (Marsh *et al.* 2013). Over the lifespan of the drought, the Chalk was the worst affected aquifer system (Marsh *et al.* 2013).

The termination of the drought was remarkable, and while huge recoveries in many groundwater levels were seen in short periods of time (see Marsh *et al.* 2013), recording above average or new maxima by August, the slowly responding groundwater levels in the Permo-Triassic Sandstone of the Midlands did not reach monthly averages until April 2013 (Marsh *et al.* 2013).

2.9.7 Relationship with meteorological drivers

The drought was caused by the persistence of anticyclonic weather conditions, resulting in a much more northerly position of the Jet Stream (Kendon *et al.* 2013). The 2010-2012 period was characterised by limited winter rainfall over successive years, along with large spatial and temporal variations in rainfall. There was also a lack of hot, dry summers, and rainfall during summer months was near to average (Marsh *et al.* 2013). The drought began with rainfall deficiencies from December 2009 to June 2010 that impacted North West England, before an exaggeration of the Northwest/Southeast rainfall gradient caused impacts to be felt the most in areas where groundwater is the major source of water supply (Marsh & Parry, 2012; Marsh *et al.* 2013). There were two other periods in the main drought episode in the Anglian region (December 2010 – May 2011) and the Midlands (April – November 2011) that were confined to more localised areas (Marsh *et al.* 2013). The 24 month period ending March 2012 was the driest for at least 100 years (Marsh & Parry, 2012). By early spring 2012, soil moisture deficits were at record levels, however the end of the drought came in April, when a change in synoptic patterns caused the Jet Stream to move south, and the highest rainfall for at least 230 years was recorded (Marsh & Parry, 2012). Marsh *et al.* (2013) comment that the 2010-2012 drought end is without "modern parallel" and stress how remarkable the hydrological termination of the drought was.

2.9.8 Relationship with surface water drought impacts

As with other major droughts caused by a lack of winter rainfall over successive years, there was a large contraction in the stream network (the worst for at least 50 years) and the cessation of flow in many winterbournes (Marsh *et al.* 2013). Most groundwater and hence surface water impacts associated with groundwater were worse towards the end of the drought period, as the Northern and Western areas recovered through late summer and autumn 2011 (Marsh *et al.* 2013). Exceptionally low accumulated flow totals in March 2012 gave the lowest runoff on record for the UK (Marsh & Parry, 2012). Reservoirs were also affected, with some southern reservoirs at 50% of capacity by the end of the drought (Kendon *et al.* 2013). Again, areas in the North and West were replenished in 2011 while the health of surface water in the South and East deteriorated (Marsh *et al.* 2013).

2.9.9 Relationship with other environmental, agricultural, economic and social impacts

The impacts associated with the 2010-2012 drought were widespread, and in some cases, severe. Marsh *et al.* (2013) reports on all these impacts, including the deterioration of river and wetland water quality through low oxygen levels, decreased effluent dilution and algal blooms, the loss of habitat and fish kills due to stream network shrinkage and the impact on farming through low soil moisture. There were also issues for the railway system posed by ground shrinkage (Marsh *et al.* 2013).

2.9.10 Water resource management and legislative responses

The use of water resource management schemes within the drought increased towards the end of the period as regions where water demand is the highest became more severely affected. Marsh *et al.* (2013) provide a comprehensive view of the mitigation procedures used, including low flow augmentation, tankered supply, the exploitation of emergency groundwater sources, Drought Orders, public appeals and hosepipe bans that affected 20 million people by April 2012. During the early part of the drought that was focussed on the North West, hosepipe bans were introduced in June 2010 (Marsh *et al.* 2013).

3 Drought classification and conclusions

3.1 LITERATURE

The literature and data available for each drought varied greatly. In general, post-1976 there was improved reporting, with Marsh *et al.* (1994, 2007, 2013), Marsh (1995, 2004, 2007), Marsh & Turton (1996), Rodda & Marsh (2011) and Kendon *et al.* (2013), all covering major droughts since then with a detailed summary. Prior to 1976, reporting, particularly with respect to groundwater, is largely diminished, and decreases with age. In addition, the more extreme the drought and the greater the public awareness of the drought, the more information there is for those periods (e.g. 1976, 2003-2006, 1890-1910). In the case of older droughts, British Rainfall publications, alongside anecdotal evidence, provides the majority of information which then had to be related to the limited borehole data of the period. Generally, the greater the aridity and surface water impacts associated with a drought, the more it appears in the literature. As this report focusses on groundwater, there are several episodes, such as the 1913-14 and 1964-65 which are widely underreported. In an attempt to reverse this discourse, an investigation into the widely reported drought of 1959 that had severe surface water impacts but little impact on groundwater is also included (see Appendix 1). The public perception, and also to some extent the academic discourse, is highly linked to dry, hot summers and not dry winters which tend to propagate groundwater droughts. As a result, the droughts with marginal surface water impacts but large groundwater impacts tend to be underreported. This is demonstrated in the 1964-65 drought, which recorded the 3rd driest year since 1887 and ranks as the 2nd most intense northern drought but is almost completely unreported in the literature.

The review of the literature also highlighted discrepancies between the perceived drought and the actual state of groundwater resources, most notably in 2003-06 and between 1988 and 1998. The literature reports the 2003-06 drought as two separate events, however an assessment of the SGI and groundwater data indicate that these two events were highly linked. This could be a reflection of the tendency to focus mainly on surface water impacts. For the period from July 1988 to January 1998, Dalton Holme records just 9 months where the SGI is a positive value (Bloomfield & Marchant, 2013). This reflects a very different situation to the one given in the literature. When considering only the Dalton Holme SGI time series, one might be tempted to classify the 1988-1998 period as one long drought episode. However, the Dalton Holme borehole gives an incredibly localised view. Whether this is representative of very specific local geology, the borehole itself, the meteorology of this eastern and sheltered part of the country, or all three, is unclear.

3.2 DROUGHT CLASSIFICATION

There have been many attempts to classify drought in the UK, however they are mainly related to weather type (Lloyd-Hughes & Saunders, 2002; Wedgbrow *et al.* 2002; Hannaford *et al.* 2011; Parry *et al.* 2010; Fleig *et al.* 2011; Kingston *et al.* 2013) or hydrological and groundwater processes on a catchment scale (Peters, 2003; Peters *et al.* 2003, 2005, 2006; Tallaksen *et al.* 2006, 2009; van Lanen *et al.* 2013). There is as yet no definitive groundwater drought classification system for the UK.

From a review of the literature, no specific drought classification can be derived. There are many character traits of drought periods in the UK that are well documented including the exaggeration of the Northwest/Southeast rainfall gradient, the propagation of drought over successive winters, and summer aridity. All major drought periods exhibit at least one of these traits. However, this is not a classification system, as they are qualities that are intrinsic to drought in the UK and they often occur independently of one another and in no discernible pattern. They are all associated with anticyclonic weather which is the main driver for drought in the British Isles.

There are some general patterns in the findings of this report, demonstrating that groundwater droughts that display limited surface water impacts tend to be underreported, despite sometimes being associated with large rainfall deficiencies. These droughts tend to be focussed in the North East, rather than the South and over a single winter. This could be a reflection of the use of groundwater resources within these areas, along with higher demand in the South of England.

In the absence of a definitive classification system, a matrix has been compiled with parameters important to groundwater drought. These have been selected due to their inherent simplicity and objectivity when compared with other parameters. Although not applicable to all droughts, the SGI in the location where the drought was most intense has also been included for ease of comparison of drought severity.

Table 3: Summary of the nine groundwater drought events.

	Multi-winter	Surface water impacts reported	Region	Cumulative SGI
1890 - 1910	✓	✓	National (S + E)	N/A
1913 - 1914	✗	✗	NE	0.17 (S) / -1.11 (N)
1933 - 1935	✗	✓	S + SE	-1.36 (S) / -0.41 (N)
1964 - 1965	✗	✗	NE	-0.24 (S) / -1.30 (N)
1975 - 1976	✗	✓	National (S + E)	-1.81 (S) / -1.23 (N)
1988 - 1993	✓	✓	SE + E	-0.71 (S) /-1.53 (N)
1995 - 1998	✓	✓	N/SE	-1.25 (S) / -1.23 (N)
2003 - 2006	✓	✓	National/SE	-1.14 (S) / -0.40 (N)
2010 - 2012	✓	✓	NW/SE	N/A

Note: in the 'Region' column the brackets denote national drought impacts, focussed in the bracketed region and a solidus indicates a change in drought focus from one region to another. In the 'SGI' column (N) denotes Dalton Holme record and (S) Chilgrove House record.

Appendix 1

This appendix covers the most recent drought period that is reported in the literature but is excluded from the drought episodes list based on a low SGI drought intensity value.

THE 1959 DROUGHT

The 1959 drought was most severe in eastern, central and north-eastern England, with a significant spatial variation in intensity (Marsh *et al.* 2007). It was a short, intense, 3 season drought, extending from February to November 1959, and exhibited record rainfall minima in September 1959 (Alexander & Jones, 2001; Marsh *et al.* 2007). There were widespread surface water impacts requiring in excess of 50 Drought Orders, the transfer of water by tanker and bulk transfers of water (Taylor *et al.* 2009). The drought affected both rural and urban communities and had impacts on the public discourse of drought, as well as highlighting the spatial scale of water control (Taylor *et al.* 2009).

Although this drought is observed in the SGI, the signal is not particularly strong, with an average of -0.66 at Dalton Holme (Bloomfield & Marchant, 2013). It does not appear in a list of major droughts when classified by the SGI (Bloomfield & Marchant, 2013) however it is classified by Marsh *et al.* (2007). This is due to several factors, including the presence of, although below average recharge in winter 1958/59, a particularly wet end to 1958 allowing for adequate recharge despite the recharge season being cut short in 1959, as well as the short duration but high intensity of the drought. The drought was also terminated in autumn 1959 (Met Office, 1963), allowing for a prompt start to the recharge season. Although the recharge season was cut short in 1959, groundwater levels were high enough to absorb the impact of a particularly dry summer and autumn, highlighting the importance of dry winters in propagating groundwater drought.

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Figure 3: Rainfall Winter (Nov–Jan) rainfall deficiencies during the 'Long Drought' in South East England	Marsh, T., Cole, G., & Wilby, R. (2007). Major droughts in England and Wales, 1800–2006. Weather, 62(4), 87-93.
Figure 4: Reporting of drought in an Australian newspaper, 1913.	National Library of Australia
Figure 6: Reporting of the 1933 Drought in a US newspaper.	The Tuscaloosa News, Jun 18th 1934. Google News.
Figure 15: Barden reservoir, Yorkshire in 1995.	**© Copyright Stephen Craven and licensed for reuse under this Creative Commons Licence**[1]
Figure 17: Parched field near Bury St Edmunds, 2006	**© Copyright Bob Jones and licensed for reuse under this Creative Commons Licence**[1]
Figure 19: A dry river bed in Hampshire, 2012.	BGS Image

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