Multi-annual droughts in the water-stressed English Lowlands: long-term variability and climate drivers

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Abstract The English Lowlands is the most populated part of the UK, and parts of the region are already water-stressed. The region is heavily dependent on groundwater resources, and is thus vulnerable to long, multi-annual drought episodes that include dry winters (winter being the time groundwater is replenished). This study uses a range of meteorological and hydrological datasets to characterise multi-annual droughts in the region from 1910 to 2012. As a prelude to a wider study of climate drivers affecting these historical long droughts, the role of ENSO in affecting dry winters in the English Lowlands is investigated. Many historical long droughts are associated with La Nińa episodes, although the relationship is complex and more work is required to disentangle the many climatic drivers of multi-annual droughts in this region.

Key words drought; UK; precipitation; river flow; groundwater; Standardized Precipitation Index; ENSO

INTRODUCTION

In early 2012, much of England was in a severe drought situation following one of the driest two-year rainfall sequences on record. While the impact on water resources was not as extensive as feared, thanks to the dramatic termination of the drought before summer 2012, the drought had major impacts on agriculture and the environment (Kendon *et al*., 2013). The drought once again brought into focus the vulnerability of the lowland areas of south and east England to prolonged rainfall deficits. The region is already the driest part of the UK and is projected to become appreciably warmer and drier in future, and will face increased drought severity according to scenario-based climate change analyses (e.g. Burke *et al*., 2010; Jackson *et al*., 2011). Parts of the region are water-stressed (Environment Agency, 2008) and the region is facing a wide range of other pressures, including an expanding population and attendant intensification in the exploitation of water resources; all of which implies major challenges to future water resource management. A number of recent droughts have raised speculation as to whether droughts have become more severe, and if so whether they have been influenced by climate change, long-term climatic variability (e.g. related to atmospheric circulation) or a combination of both. In the wake of the 2010–2012 drought, a collaborative study was initiated by the UK Met Office, Centre for Ecology and Hydrology and British Geological Survey. This aims at characterising multi-annual droughts in Lowland England in the 20th and early 21st centuries, and their potential climatic drivers. This short paper presents preliminary results of this collaboration.

DATASETS AND METHODOLOGIES

Study area

The focus of this study is on the English Lowlands. This area, comprising the English Midlands, southeast England and East Anglia, is defined by its geographical, climatological and hydro-geological characteristics, rather than being an administrative entity. Figure 1 shows a map of the UK which illustrates the locations of major aquifers and shows Lowland England outlined. As the most populated part of the UK, with low annual average rainfall (680 mm as a 1961–1990 long-term areal average for Lowland England) and often permeable catchment characteristics, particularly Chalk, this area is vulnerable to multi-annual droughts affecting groundwater

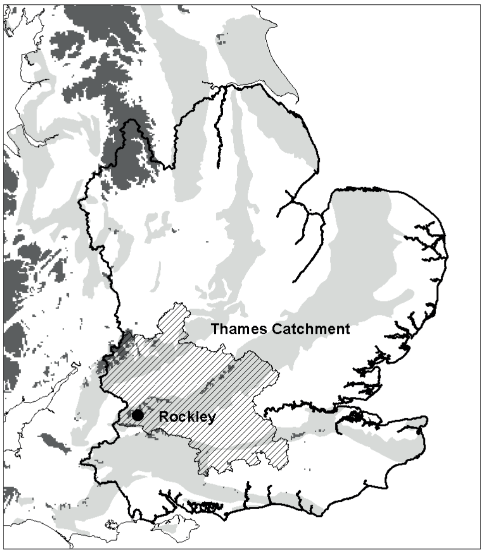


Fig. 1 location map showing the English Lowlands region (dark line), major aquifers in the English Lowlands (light grey) and land above 200 m (dark grey). The outline of the Thames catchment and the location of the Rockley borehole are shown.

resources. Of particular concern are droughts resulting from extended rainfall deficiencies including dry winter periods; the winter half-year being the main period for groundwater recharge.

Datasets

A range of hydro-meteorological datasets have been used to identify multi-annual droughts through the instrumental record. For rainfall, the key dataset used was a monthly 5 × 5 km resolution gridded dataset from 1910 to date, assembled using the methods of Perry & Hollis (2005). This gridded dataset forms the basis of official UK rainfall statistics produced by the Met Office National Climate Information Centre (the "NCIC rainfall"). Also used, in Fig. 4, is the TS3.10 0.5° × 0.5° resolution global land surface rainfall data set (Harris *et al*., 2013) and, in Fig. 5, the HadCRUT4 land surface air temperature and sea surface temperature data set (Morice *et al*., 2012). River flow and groundwater level data were taken from the UK National River Flow Archive (NRFA) and National Groundwater Level Archive (NGLA). An NRFA regional runoff dataset for the English Lowlands is available to characterise total outflows from the region from 1961 to 2012 (Marsh & Dixon, 2012). The series is based on aggregated flows from large rivers and uses hydrological modelling to account for ungauged areas. The boundary shown in Fig. 1 was used to create the "English Lowlands" NCIC Rainfall and NRFA Regional Runoff series used in this paper. In addition, the Thames at Kingston flow record, the longest on the NRFA, from 1883 to present, provides a temporal coverage comparable with that of NCIC rainfall. This series is naturalised to remove the influence of abstractions. The longest Chalk groundwater level record (starting 1932) from the Thames catchment, the Rockley borehole series, is also used.

Methods of drought identification

As a first step in identifying major multi-annual rainfall droughts in lowland England, monthly rainfall deficits were calculated (the monthly areal rainfall total minus the monthly long term average). These deficits were accumulated over rolling multi-month time periods from 12 to 24 months long (the droughts identified actually lasted between 13 months and 26 months). The following criteria were then used to identify key droughts in three categories of severity:

(a) Category 1: Occurrences of rainfall deficits of over 270 mm (40% of annual average rainfall) over 12 to 24 months time-scales where this magnitude of deficit persisted for one or more months;

(b) Category 2: Occurrences of rainfall deficits of over 220 mm (32% of annual average rainfall) over 12 to 24 months time-scales which persisted for one or more months, or deficits of over 200 mm (28% of annual average rainfall) which were longer lasting; and
(c) Category 3: Notable occurrences of rainfall deficits of over 170 mm (25% of annual average rainfall) over 12 to 24 months time-scales.

The widely-used Standardized Precipitation Index (SPI) was used to examine the impact of these meteorological droughts on river flow and groundwater. The SPI is the unit normal transformation of the time-averaged precipitation time series climatologically appropriate to the particular location and time of year – full details can be found in McKee *et al*. (1993). The SPI has recently been modified for application to flow and groundwater series, but there is currently no consensus as to an appropriate methodology. In this study the standard SPI approach (based on fitting a gamma distribution) was used. Cumulative distribution plots showed this approach was reasonable for the flow time series but less appropriate for groundwater. SPI is typically calculated over a range of durations (6, 9, 12, 18, and 24 months); in this study, focusing on long droughts, the 18-month SPI (SPI-18) was used for precipitation, with SPI-12 selected for flow and groundwater as these had the closest correlation with SPI-18.

RESULTS

Major rainfall droughts

Based on the criteria listed above 15 notable droughts were identified since 1910, each with a duration of at least one year and encompassing at least one winter period – i.e. likely to be of significant impact to groundwater resources. The final list of key Category 1, 2 and 3, 13 to 26 month droughts across Lowland England is presented in Table 1.

Table 1 Key 13 to 26 month duration droughts across Lowland England, 1910 to present, based on NCIC gridded rainfall data.

Category	Start month	End month	Duration (months)	Total rainfall (mm)	1961–1990 average (mm)	Deficit (mm)	% of Average
1	Aug-1920	Dec-1921	17	630	991	361	64
1	Apr-1933	Nov-1934	20	829	1133	304	73
1	May-1975	Aug-1976	16	541	898	357	60
1	Mar-1990	Feb-1992	24	1006	1361	354	74
1	Apr-1995	Apr-1997	25	1004	1411	407	71
1	Apr-2010	Mar-2012	24	1050	1361	311	77
2	Feb-1943	Jun-1944	17	662	937	276	71
2	Aug-1947	Sep-1949	26	1181	1478	296	80
2	Dec-1963	Feb-1965	15	639	855	215	75
2	Aug-1972	May-1974	22	995	1255	260	79
2	Aug-1988	Nov-1989	16	702	924	222	76
2	Nov-2004	Apr-2006	18	810	1025	215	79
3	Apr-1928	Sep-1929	18	782	1006	224	78
3	Jun-1937	Jun-1938	13	556	735	179	76
3	Feb-1962	Feb-1963	13	556	726	170	77

Key droughts across Lowland England since 1910 identified above include 1920–21, 1933–34, 1975–76, 1990–92, 1995–97, consistent with earlier studies (Marsh *et al*., 2007, Bloomfield & Marchant, 2013). Of these droughts, the 1975–76 drought is generally regarded as the benchmark across much of England and Wales against which other droughts are typically compared – in only this and the 1920–21 drought were rainfall totals on this time-scale below 65% of average (Table 1). The 2010 to 2012 event is amongst the most significant prolonged droughts of the last century.

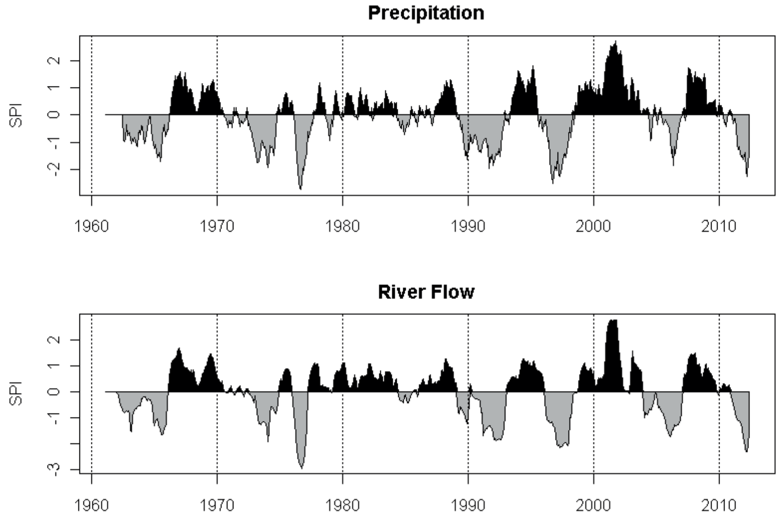


Fig 2 SPI-based droughts for NCIC rainfall and NRFA Regional runoff for the entire English Lowlands region, using SPI18 for precipitation and SPI12 for runoff.

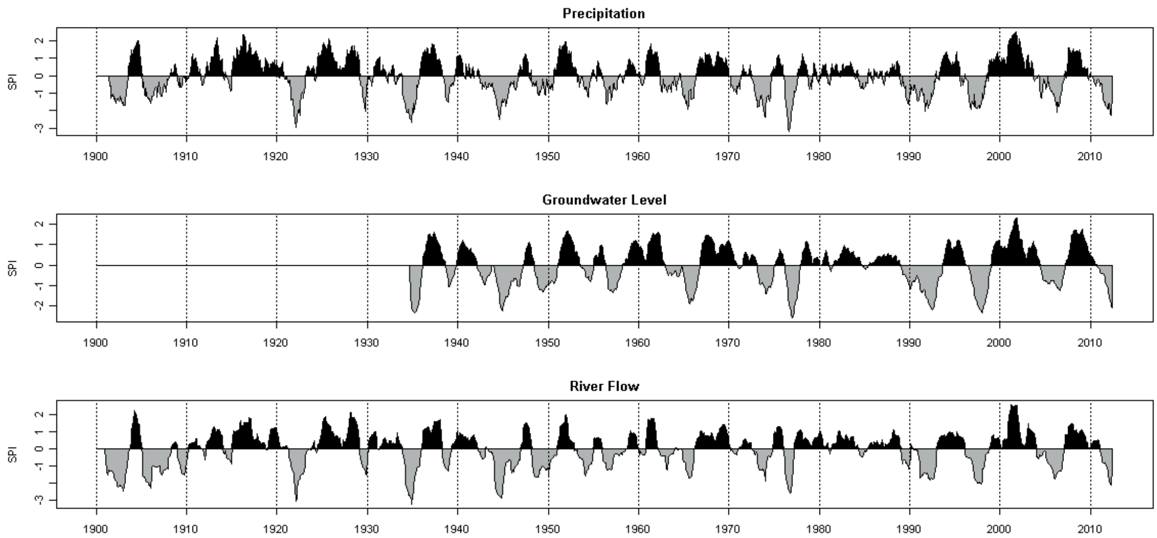


Fig 3 SPI-based droughts for the Thames catchment, using SPI18 for precipitation, and SPI12 for groundwater levels (Rockley borehole) and river flow (Thames at Kingston, UK).

Droughts in river flow and groundwater

The SPI analogue droughts for the English Lowlands rainfall and runoff series are presented in Fig. 2. The most severe prolonged runoff droughts are the four Category 1 droughts (1976, 1992, 1997, 2012). The 2004–2006 event is a more severe river flow drought than precipitation alone suggests; the long droughts of the early 1960s and early 1970s are also clear from the flow series.

The SPI-based precipitation, groundwater level and river flow droughts for the Thames catchment are presented in Fig. 3. These plots show that many of the most severe multi-annual rainfall droughts correspond well: the lowest SPI values for river flow are for 1934 (Category 1), 1976 (Category 1), 1944 (Category 2), 1921 (Category 1), 2012 (Category 1), 1992 (Category 1) and 1997 (Category 1). These droughts are manifested consistently in the groundwater time series.

The results confirm that there is no compelling evidence for a long-term increase in drought severity or frequency in the Thames, the largest catchment in the English Lowlands. There has been a cluster of multi-annual droughts from 1990 onwards, but many of the most severe droughts occurred pre-1950. A pattern of fewer droughts in the 1965–1990 period suggests some multidecadal variability.

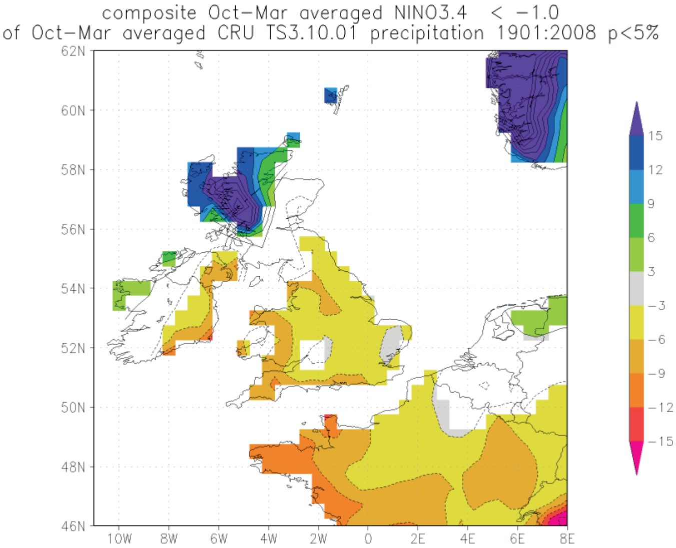
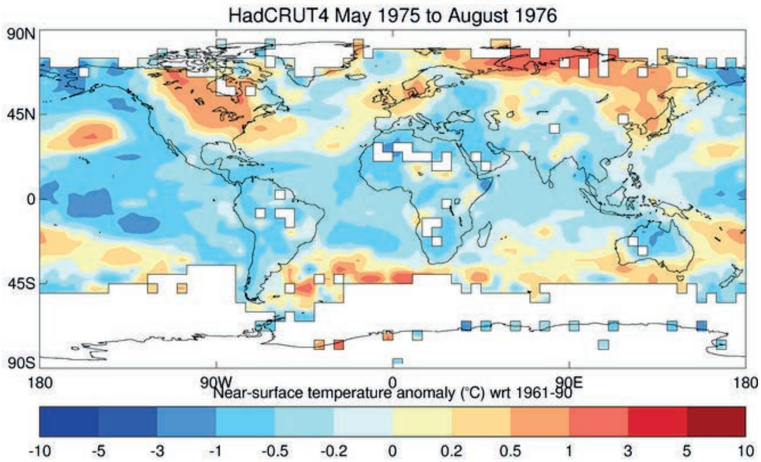


Fig. 4 Association between La Nina (average SST in the NINO3.4 region 1.0°C or more below the 1961–1990 average) and Oct–March average precipitation for the UK 1901–2008. Precipitation anomalies from a 1961–1990 average are expressed in mm/month and coloured if significant at the 5% level. The 1961–1990 average for Lowland England is around 60 mm/month, so 6 mm/month is equivalent to a 10% deficit. The NINO3.4 region is 170–120°W, 5°N–5°S.



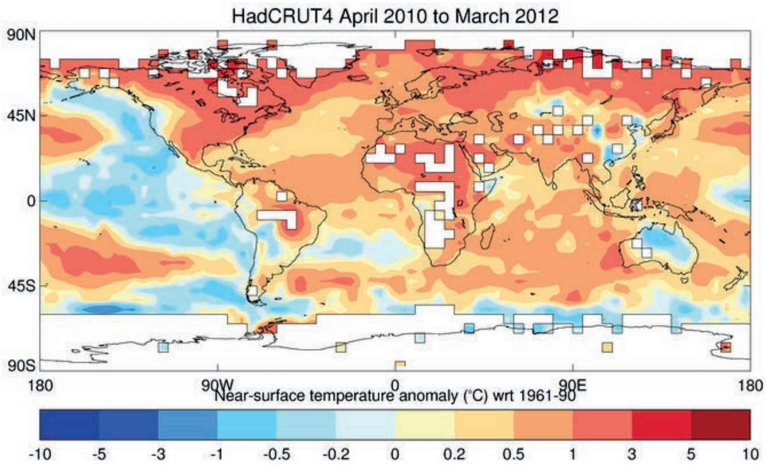


Fig. 5 Global surface temperature anomalies relative to 1961–1990 during the 1975–1976 and 2010–2012 droughts taken from HadCRUT4. Nino 3.4 had an anomaly of –0.81°C (1975–1976 drought) and –0.78°C (2010–2012 drought), quite strong signals for such long periods. La Nina ended just before the drought ended in both cases.

CLIMATIC DRIVERS: ROLE OF ENSO IN MULTI-ANNUAL DROUGHTS

A companion study (Folland *et al*., 2013) of the droughts identified in Table 1 is investigating forcing factors that may have influenced these events, via analysis of atmospheric circulation and rainfall anomalies over the UK and nearby Europe. An illustrative example of the influence of a remote forcing factor is shown in Fig 4 for the strong La Niña phase of El Nino/Southern Oscillation (ENSO) tropical Pacific sea surface temperatures (SSTs). La Niña is known to have some influence on atmospheric circulation over the UK in winter and spring (e.g. Moron & Gouirand, 2004). Figure 4 shows a significant relationship between La Niña and Lowland England rainfall deficits in the winter half-year, the most critical time for groundwater replenishment.

Clearly, this result does not imply that all winter droughts are associated with La Niña as there are many influences on UK winter climate (e.g. Folland *et al*., 2012). However, La Niña conditions occur often enough during droughts in Table 1 to merit more investigation. Two examples are shown in Fig. 5 for two Category 1 droughts. The wedge shaped cold region of SST in the tropical Pacific characteristic of La Niña is clear (n.b. the overall increase of surface temperature over much of the world between the two droughts is associated with increasing greenhouse gases). However, the fact that La Niña on its own is an insufficient indicator of drought is underlined by the fact that a moderate La Niña in the winter half year October 2000–March 2001 (SST anomaly –0.64°C) was actually associated with the wettest winter half year conditions in the English Lowlands observed since 1910. On the other hand, the coldest winter half year La Niña (October 1988–March 1989) SST anomaly –1.76°C was associated with the 11th driest winter half year rainfall total since 1910 – a period within the Category 2 drought 1988–89.

DISCUSSION AND CONCLUSIONS

This study has focused on the English Lowlands: a region that is vulnerable to long duration, multi-annual droughts that have substantial impacts on groundwater resources, and which is facing increasing pressures on water management. A range of datasets were used to characterise multi-annual droughts in the region, including the rainfall and runoff from the entire region (from 1961 to 2012). The results show that the English Lowlands has experienced a number of major multi-annual droughts, with seven such events since 1961. A cluster of multi-annual droughts is apparent from 1990 onwards, with the 2010–2012 drought being one of the most severe on record. However, longer-term analyses of river flow and groundwater level records show that there is no compelling evidence for an increase in drought occurrence, magnitude or duration since 1910, but clear evidence of interdecadal variability.

There is a need to understand the drivers of this variability in order to increase our resilience to multi-annual events through improved monitoring and outlook capabilities. The UK is subject to a complex array of climatic influences, typical of mid-latitude regions on the North Atlantic margin. The current study suggests that ENSO may also play a role in influencing many of the dry winters that are associated with the multi-annual droughts of Table 1. Ongoing research is investigating ENSO influences on Lowland England droughts in more detail, alongside other climate drivers (Folland *et al*., 2013).

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