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Increased incidence, duration and intensity of groundwater drought associated with anthropogenic warming

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Abstract. Here we present the first empirical evidence for changes in groundwater droughts associated with anthropogenic warming in the absence of significant long-term trends in precipitation. Analysing standardised indices of monthly groundwater levels, precipitation and temperature, using two unique groundwater level data sets from the Chalk aquifer, UK for the period 1891 to 2015, we describe an increase in both the frequency and intensity of groundwater drought months, and an increase in frequency, duration and intensity of episodes of groundwater drought since 1891 associated with anthropogenic warming. We also identify a transition from coincidence of episodes of groundwater drought with precipitation droughts at the end of the 19th century, to an increasing coincidence with both precipitation droughts and with hot periods in the early 21st century. In the absence either of long-term changes in precipitation deficits during episodes of groundwater drought or long-term changes in the occurrence and intensity of consecutive dry winters, we infer that the changing nature of groundwater droughts is due to changes in evapotranspiration (ET) associated with anthropogenic warming. We note that although the water tables are relatively deep at the two study sites, a thick capillary fringe of at least 30 m in the Chalk means that ET should not be limited by precipitation at either site; that ET may be supported by groundwater through major episodes of groundwater drought; and, hence, long-term changes in ET associated with anthropogenic warming may drive long-term changes in groundwater drought phenomena in the Chalk aquifer. Given the extent of shallow groundwater globally, this phenomenon may be widespread in temperate environments.

1 Introduction

Globally groundwater provides of the order of one third of all freshwater supplies (Doll et al, 2012; 2014), 2.5 billion people are estimated to depend solely on groundwater for basic daily water needs (UN, 2015), and it sustains the health of many important groundwater-dependent terrestrial ecosystems (Gleeson et al, 2012). This high level of dependence on groundwater means that communities and ecosystems across the globe are vulnerable to both natural variations in groundwater resources (Wada et al., 2010) and to the impacts of anthropogenic climate change on groundwater (Green et al., 2011; Taylor et al., 2013). Groundwater droughts, taken here to mean periods of below normal groundwater levels (Tallaksen & Van Lanen, 2004; Van Loon, 2015; Van Loon et al., 2016a; 2016b), are a major threat to global water security (Van Lanen et al., 2013) and are potentially susceptible to being modified by climate change. Since drought formation and propagation are driven by precipitation deficits and evapotranspirative losses associated with elevated temperatures, there is an expectation that global climate change, and in particular global warming is already modifying the occurrence and nature of droughts (Dai, 2011; Sheffield et al., 2012; Trenberth et al., 2014; Greve et al., 2014).However, to date there have been no systematic investigations of how anthropogenic climate change may affect groundwater drought (Green et al., 2011; Taylor et al., 2013; Jackson et al., 2015) and it has been noted in the IPCC Fifth Annual Assessment of Impacts, Adaptation, and Vulnerability that: 'there is no evidence that … groundwater drought frequency has changed over the last few decades' (Jiménez Cisneros et al., 2014, p.232). This significant gap in our understanding of groundwater drought is not surprising given the limited availability of long groundwater level time series suitable for analysis (Jimenez Cisneros et al., 2014) and the low signal to noise ratios characteristic of many hydrological systems (Wilby 2006; Watts et al., 2015). In addition, the challenges of formal attribution of groundwater droughts due to global (or anthropogenic) warming (Trenberth et al., 2015), and the potentially confounding influences of land use change and groundwater abstraction on groundwater drought (Stoll et al., 2011; Jimenez Cisneros et al., 2014; Van Loon et al., 2016a; 2016b) complicate any analysis of such droughts. Here we address some of these challenges and present the first empirical evidence for the effects of anthropogenic warming on the changing nature groundwater droughts.

Groundwater systems have been shown to effect global land-energy budgets and regional climate (Senevirante et al., 2006; Trenberth et al., 2009; Maxwell and Condon, 2016) and can control the generation of large-scale hydrological droughts, particularly in temperate climates (Van Lanen et al., 2013). Although the role of evapotranspiration (ET) in regional- to global-scale drying is still a matter of active debate (Dai, 2011; Sheffield et al., 2012; Greve et al., 2014; Milly and Dunne, 2016), there is an expectation of a general increase in ET, and hence of general drying associated with human-induced global warming (Trenberth et al., 2014), and even if heating from anthropogenic warming may not necessarily cause droughts, Trenberth et al. have noted that it is expected that when droughts do occur that they are likely to set in more quickly and to be more intense in a warming world (Trenberth et al., 2014). In order to investigate the evidence for such changes in groundwater droughts it is necessary to identify sites from unconfined aquifers with long, continuous records of groundwater levels where there have been no systematic long-term changes in precipitation or land cover. In addition, the sites should be free from the systematic, long-term influence of groundwater abstraction. Two such sites, representative of groundwater systems in temperate climates, have been identified from the Cretaceous Chalk, the major aquifer of the UK. These sites are at Chilgrove House (CH), believed to be the world's longest continuously monitored groundwater level observation borehole, and at Dalton Holme (DH).

We have adopted an approach similar to that of Diffebaugh et al. (2015) in order to investigate how anthropogenic warming may have effected groundwater droughts at CH and DH. Diffebaugh et al., (2015) demonstrated how anthropogenic warming has increased hydrological drought risk in California over the last approximately 100 years by comparing the changing frequency of drought, as measured by the Palmer Modified Drought Index (PMDI), with standardised annual average precipitation and temperature anomalies. Here, instead of using the PMDI, we use the Standardised Groundwater level Index, SGI (Bloomfield and Marchant, 2013), to characterise the monthly status of groundwater, and compare changes in SGI with changes in standardised monthly air temperature and precipitation. We have chosen not to use the Standardised Precipitation Evapotranspiration Index, SPEI, (Vincente-Serrano SM et al., 2010; Trenberth et al., 2014) in our analysis as we explicitly wish to analyse the correlations between SGI and standardised temperature and SGI and standardised precipitation independently (Stagge et al., 2017). We have not attempted to formally attribute any groundwater droughts to climate change. Rather, we follow the approach of Trenberth et al. (2015) and investigate how climate change may modify a particular phenomenon of interest. In our case, given the known centennial-scale anthropogenic warming over the UK described in section 2.2 (Sexton et al., 2004; Karoly and Stott, 2006; Jenkins et al., 2008), using an empirical analysis we address the question: how has the occurrence and intensity of groundwater drought, as expressed by changes in SGI, changed over the same period? Although the analysis is restricted to data from two sites in the UK, the findings have potentially significant implications for changes in groundwater drought driven by anthropogenic warming given the global extent of shallow groundwater systems (Fan et al., 2013).

2 Site descriptions & drought context

The sites used in this study are unusual due to the length, continuous nature and frequency (monthly or better) of the groundwater level observations. However, they are representative of groundwater systems and hydrological settings that are common throughout large, populous areas of the globe including Europe, Asia, N. and S. America and parts of Australia and southern Africa, i.e. they represent shallow, unconfined aquifers in temperate regions.

2.1 Site descriptions

The Chilgrove House (CH) and Dalton Holme (DH) groundwater observation boreholes are located in the Chalk, the principal aquifer in the UK (Downing et al., 1993; Lloyd, 1993). CH is in south-east England and DH in the east of England (Figure 1). The CH and DH hydrographs are the two longest, continuous records in the UK's National Groundwater Level Archive (NGLA) (British Geological Survey, 2017). Hydrographs such as these in the NGLA are taken to be representative of the major UK aquifers, in this case of the Chalk aquifer, and were selected to being in areas least affected by abstraction (Jackson et al., 2015). There are no major groundwater abstractions in the immediate vicinity of the observation boreholes. Both observation boreholes are located in small rural catchments with no major population centres or industrial activities, and there has been no long-term change in land use in the catchments over the study period. The inference of a lack of any systematic impacts from abstraction on groundwater levels at CH and DH is supported by the observed correlation between precipitation and groundwater levels at the two sites (Bloomfield and Marchant, 2013).

CH is a 62.0 m deep observation borehole in the Seaford Chalk Formation, a white chalk (limestone) of Coniacian to Santonian age. Groundwater levels over the observation record have an absolute range of about 43.7 m, with a maximum groundwater level of about 77.2 meters above sea level (masl) and a minimum level of about 33.5 masl, equivalent to <1 m to about 43 m below ground level at the site (Supplementary Information, Figure S1). The hydrograph generally has an annual sinusoidal response, typical of unconfined Chalk, with an annual groundwater fluctuation of around 25 m, although double and higher multiple recharge peaks and episodes are also relatively frequent due to natural variability in precipitation (recharge can occur in summer as well as winter with appropriate antecedent conditions and precipitation). Variability in winter recharge means that in some winters, such as 1854-5, 1897-8, 1933-4, 1975-6, 1991-2 and 1995-6, minimal recharge occurs.

This characteristically results in a nearly continuous decline in groundwater levels throughout the recharge season, and in all cases groundwater droughts occurred during the following summers. There are no clear geological or catchment constraints on either the lowest or highest groundwater levels at CH. However, the River Lavant, approximately 2 km to the south-east of the CH borehole, is a Chalk bourne stream that drains the catchment. The flowing length and discharge of the Lavant reflect the regional groundwater level. Land cover in the Lavant catchment is approximately 35% woodland, 65% arable and grassland with a small number of villages. Comparison of Ordnance Survey land cover mapping from 1898 and 2015 shows that there has been no substantial change in land cover in the vicinity of CH during this period (Ordnance Survey, 1897; 2015).

DH is a 28.5-m-deep observation borehole in the Burnham Chalk Formation, a thinly-bedded white chalk of Turonian to Santonian age. Groundwater levels have a range of 14.8 m, with a maximum groundwater level of about 23.8 masl and a minimum of about 9.6 masl, equivalent to a range from about 10 m to about 25 m below ground level (Supplementary Information, Figure S1). The groundwater level hydrograph has a broadly sinusoidal appearance. Groundwater levels at DH respond more slowly to rainfall than at CH, despite the thinner unsaturated zone. This is probably due to local effects of thin glacial till deposits near DH. Maximum groundwater levels at DH may be controlled by the elevation of springs that feed a small surface drain about 0.75 km to the south. There are no clear geological or catchment constraints on the lowest groundwater levels. DH is located in a flat lying area with no major streams or rivers. Land cover in the immediate vicinity of DH is predominantly arable and grassland with a number of small areas of woodland and villages. Comparison of Ordnance Survey land cover mapping from 1892 and 2015 shows that there has been no substantial change in land cover during this period (Ordnance Survey, 1911; 2015).

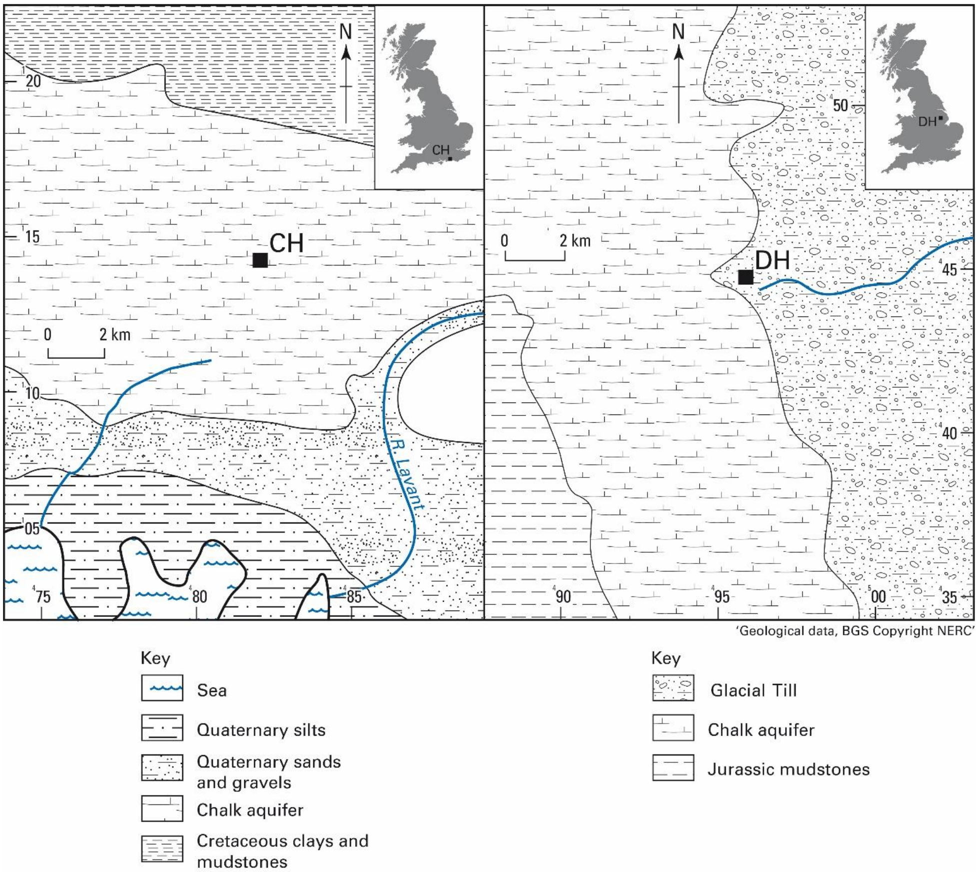

Figure 1. Location of the CH and DH observation boreholes, local geological setting, coastline and surface water courses.

2.2 Climate & drought context

Average monthly air temperature at CH over the observation record from 1891 to 2015 is 9.4°C and at DH it is 9.1°C, with maximum and minimum average monthly temperatures of 19.8°C and 18.8°C and -3°C and -1.6°C at CH and DH respectively (Supplementary Information, Figure S2). In the Köppen–Geiger classification (Peel et al., 2007), the climate at CH and DH can be characterised as temperate and falls in the ocean or maritime climate category, being representative of large parts of north-west Europe. Mean monthly precipitation at CH is 83 mm, slightly higher than at DH where the mean monthly precipitation is 58 mm.

Air temperature across both catchments closely follows the Central England Temperature (CET) monthly series (Parker et al., 1992) (Supplementary Information, Figure S2). Analysis of the CET record shows that near-surface air temperature in England has been rising at a rate of 0.077°C/decade since 1900 (Parker & Horton, 2005) and by about 0.42°C/decade between 1975 and 2005 (Karoly and Stott, 2006), and the observed recent warming in mean annual CET has been inferred to be due to anthropogenic forcing (Sexton et al., 2004; Karoly and Stott, 2006; Jenkins et al., 2008; King et al., 2015). In contrast, annual mean precipitation over England shows no systematic trends since records began in 1766, and there has been no attribution of changes in annual mean precipitation to anthropogenic factors (Jenkins et al., 2008; Watts et al., 2015). Precipitation in the UK is, however, seasonal and highly variable, with a tendency towards dryer summers in the south-east and wetter winters in the north-west (Jenkins et al., 2008; Watts et al., 2015).

The precipitation time series at CH and DH show seasonal and inter-annual variations, including episodes of meteorological drought consistent with the broad drought history of southern and eastern England (Supplementary Information, Figure S3). A number of studies have described major episodes of hydrological drought, including groundwater drought, in the UK since the 19th Century (Marsh et al., 2007; Lloyd-Hughes et al., 2010; Bloomfield & Marchant, 2013; Bloomfield et al., 2015; Folland et al., 2015) and the societal impacts of those droughts (Taylor et al., 2009; Lange et al., 2017). Marsh et al. (2007) identified seven episodes of major hydrological droughts in England and Wales between 1890 and 2007 using ranked rainfall deficiency time series and analysis of long river flow and groundwater level time series (Marsh et al., 2007, Table 2) as follows: 1890-1910 (known as the 'Long Drought'); 1921-1922; 1933-34; 1959; 1976; 1990-92; and 1995-1997. Marsh et al. (2007) noted that of these major droughts, all but one, the drought of 1959, had sustained and/or severe impacts on groundwater levels. All the major droughts typically had large geographical footprints extending over much of England and Wales as well as over parts of north western Europe (Lloyd-Hughes and Saunders, 2002; Lloyd-Hughes et al., 2010; Fleig et al., 2011; Hannaford et al., 2011). However, regional variations in drought intensities were present within and between the major drought events as function of spatial differences in driving meteorology and catchment and aquifer properties (Marsh et al., 2007; Bloomfield & Marchant, 2013; Bloomfield et al., 2015).

The three periods used for analysis in this study, 1891-1932, 1933-1973 and 1974-2015 (section 3), each contain notable episodes of historic drought. For example, the first analysis period includes the 'Long Drought' of 1890-1910 (Marsh et al., 2007), the middle period includes the drought of 1933-1934, the most intense groundwater drought on record at CH, and the last period includes the 1975-1976 drought a major groundwater drought at both CH and DH (Bloomfield & Marchant, 2013).

3 Data & methods

3.1 Data

Groundwater level measurements are available back to 1836 for the observation borehole at CH, while groundwater levels are available for DH back to 1889. We have chosen to analyse the 125-year-long series of observed monthly groundwater levels from 1891 to 2015 common to both sites. The groundwater level data have been taken from the National Groundwater Level Archive, NGLA (National Groundwater Level Archive, 2017). Groundwater level observations are typically at least at monthly intervals. Groundwater levels have been linearly interpolated to the end of the month prior to standardisation, as the SGI requires groundwater level data on a regular time step.

Average monthly air temperature and total monthly precipitation are from the Met. Office UKCP09 gridded (5 km x 5 km) observation dataset (Met. Office, 2017). Temperature and precipitation data have been extracted for the grid cell in which the CH and DH observation boreholes are located. Published temperature and precipitation data are available for the period 1910 to 2011 (Met. Office, 2017). The work described here is part of a Natural Environment Research Council (NERC) funded Historic Droughts project (see Acknowledgements) that includes work to extend records back to 1891 using newly recovered, digitised and gridded meteorological records, and extended to 2015 using unpublished updates.

3.2 Methods

The empirical analysis described in this paper broadly follows the approach of Diffebaugh et al., (2015), i.e. analyses changes in the frequency and co-occurrence of three standardised indices with time, where one index is a measure of the droughtiness of the system and the other two indices separately characterise precipitation and air temperature anomalies. Diffebaugh et al., (2015) chose to analyse their 100-year-long records in two halves. However, in this study three periods have been used for the analysis, 1891-1932, 1933-1973 and 1974-2015. This means that the last period, 1974-2015, coincides with the period of greatest documented anthropogenic warming over the study area (Karoly and Stott, 2006). In addition, the use of three periods for analysis provides more granularity in the description of changes in the standardised indices with time.

The Standardised Groundwater level Index, SGI (Bloomfield and Marchant, 2013), is used to characterise monthly status of groundwater, and compare changes in SGI with changes in standardised monthly air temperature and precipitation. The SGI builds on the Standardised Precipitation Index (SPI) of McKee et al. (1993) to account for differences in the form and characteristics of groundwater level time series. The SPI was proposed by McKee et al. (1993) as an objective precipitation-based measure of the severity and duration of meteorological droughts. It assumes that drought status is described by a normally distributed index. However, Bloomfield and Marchant (2013) demonstrated that parametric transformations of groundwater levels typically produced poor approximations to normal distributions, and concluded that it is doubtful if the resulting standardised series could be objectively compared. Instead Bloomfield and Marchant (2013) recommended a non–parametric approach to the standardisation of groundwater level hydrographs similar to other non-parametric approaches, for example Osti et al. (2008) who used a plotting position method to estimate a standardised precipitation, and Vidal et al. (2010) who used a non-parametric kernel density fitting routine to estimate a normalised soil moisture index.

SGI has been estimated using the monthly groundwater level time series. The SGI relies on a non–parametric approach to the standardisation of groundwater level hydrographs (Bloomfield and Marchant, 2013). It is estimated using a normal-scores transform (Everitt, 2002) of groundwater level data for each calendar month. This nonparametric normalisation assigns a value to observations, based on their rank within a data set, in this case groundwater levels for a given month from a given hydrograph. The normal scores transform is undertaken by applying the inverse normal cumulative distribution function to n equally spaced p_i values ranging from $1/(2n)$ to $1-1/(2n)$. The values that result are the SGI values for the given month. These are then re-ordered such that the largest SGI value is assigned to the i for which p_i is largest, the second largest SGI value is assigned to the i for which p_i is second largest, and so on. The SGI distribution which results from this transform will always pass the Kolmogorv–Smirnov test for normality. The normalisation is undertaken for each of the 12 calendar months separately and the resulting normalised monthly indices then merged to form a continuous SGI time series.

A Standardised Temperature Index (STI) and Standardised Precipitation Index (SPI) have been calculated by applying the SGI method to the average monthly temperature (STI) and a monthly accumulated rainfall (SPI) time series. Due to the lagged response of groundwater levels to driving meteorology (Bloomfield and Marchant, 2013; Van Loon, 2015), correlations between SGI and STI_q and SPI_q will vary with q, where q is the averaging period (for preceding months temperature) or accumulation period (for preceding months precipitation). Here we estimate Pearson cross-correlation coefficients between SGI and STI and between SGI and SPI for periods q = 1 to 12, and then search for the period q with the highest absolute summed cross-correlation (Supplementary Information, Figure S4). The optimal averaging/accumulation period was found to be 6 and 7 months for CH and DH respectively. Consequently, SPI_6 and SPI_7 have been used in the analysis of data from CH and DH respectively and in the following reporting of results and discussions all references to SPI are for those accumulation periods.

There is a plethora of definitions of meteorological drought (Lloyd-Hughes, 2014; Van Loon, 2015). Here we follow the WMO convention for SPI (McKee et al., 1993; World Meteorological Organisation, 2012) precipitation or meteorological drought is defined as any period of continuously negative SPI that reaches an intensity of -1 or less. By analogy, a period of continuously negative SGI or SPI that reaches a monthly intensity of -1 or less is defined as an episode of groundwater or precipitation drought, and a period of continuously positive STI that reaches a monthly intensity of 1 or more is defined as a hot period. In addition we are interested in the degree of co-incidence between groundwater droughts, precipitation droughts, and hot periods. Groundwater droughts have been assessed to be co-incident with precipitation droughts or with hot periods if both the following conditions are met: i.) any part of a groundwater or precipitation drought episode or hot period overlaps, and ii.) within the periods, incidents of monthly SGI $\leq$ -1 either overlap with or postdate incidents of either monthly SPI is $\leq$ -1, or monthly STI is $\geq$ 1.

3 Results

3.1 Changes in standardised monthly temperature, groundwater level and precipitation since 1891

SGI time series show that there has been a large increase in the frequency of months of groundwater drought since 1891 at both sites (Figures 2 and 3 and Supplementary Information Tables S1 and S2). The frequency of months of groundwater drought has more than doubled between the first third (1891-1932) and the last third (1974-2015) of the record, i.e. from about 10% of months at both sites in the first third of the record to 21.1% and 25.9% at CH and DH respectively in the last third of the record. The increase in frequency of groundwater drought months is associated with a very large increase in the frequency of hot months, from 4.8% to 34.4% of the months at CH and from 1.8% to 35.8% of the months at DH. In contrast, there has been no systematic change in the frequency of precipitation drought months. Given that the standardised indices are normally distributed, a null model can be estimated where each standardised index is assumed to be a realisation of temporally auto-correlated Gaussian random function (with auto-correlation function estimated from the observed data). The probability of the difference in the number of hot months in the period 1891-1932 and

1974-2015 being as extreme as the observed is < 0.001 for both CH and DH. For groundwater drought months the probabilities are 0.056 for CH and 0.055 for DH, but for precipitation drought months they are 0.76 for CH and 0.45 for DH. From this it is inferred that the increased incidence of hot months and of groundwater drought months between the start and end of the record is very unlikely to occur by chance at both sites, but that there is no significant difference in the probability of precipitation drought.

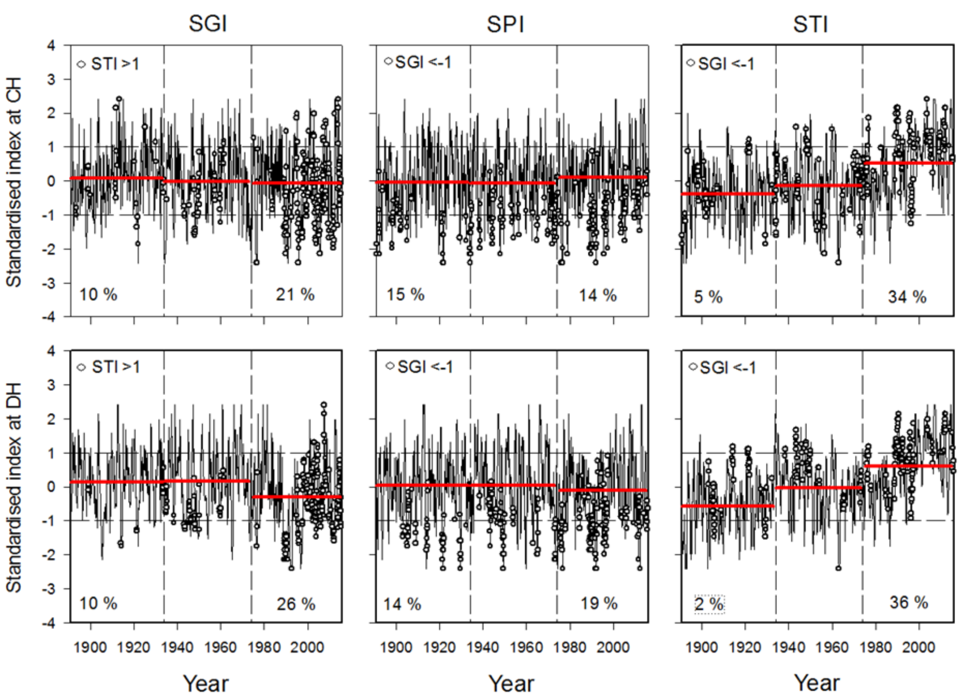

Figure 2. Changes in standardised indices of groundwater level, precipitation and temperature since 1891. Time series of SGI, SPI, and STI for CH (upper panels) and DH (lower panels) for the period 1891-2015, with 42 year running mean highlighted in blue. Open circles in plots of SGI denote months where STI is ≥ 1, and in plots of SPI and STI denote months where SGI is ≤ -1. Percentages (rounded to the nearest integer) are shown of months in the first and last third of the records where SGI and SPI are ≤ -1 and STI is ≥ 1.

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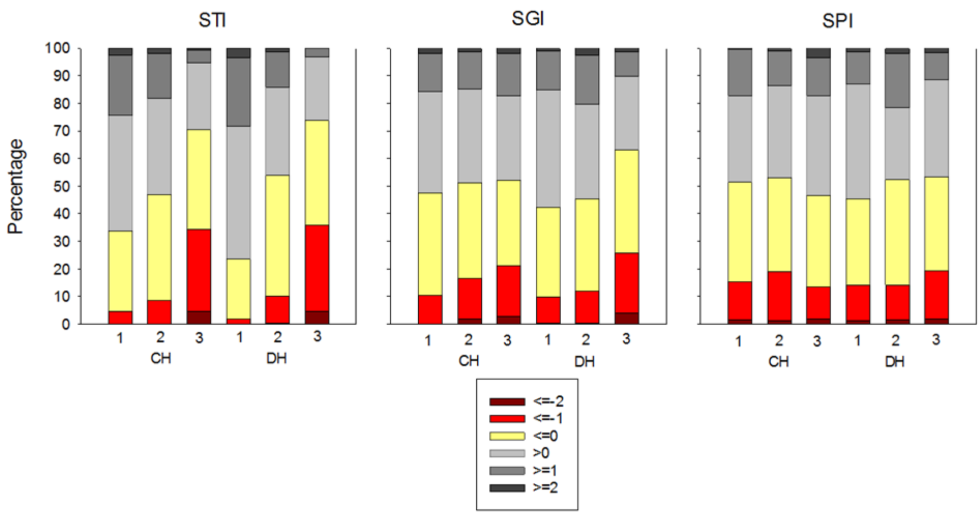

Figure 3. Percentage of monthly STI, SGI and SPI as a function of six ranges of standardised values from ≤ -2 to ≥ 2 for each third of the records from CH and DH.

3.2 Changes in association between monthly groundwater drought, temperature and precipitation

As a consequence of the increase in frequency of groundwater drought months and of hot months across the observational record, there has been a considerable increase in the number of groundwater drought months that coincide with hot months. The percentage of groundwater drought months that coincided with hot months increased from about 8% and 12% in the period 1891-1932, to about 48% and 52% in the period 1974-2015 for CH and DH respectively (Figure 4). At the same time, there has been a reduction in the coincidence of months of groundwater and precipitation drought for these two periods, from about 67% to 50% and from about 71% to 67% for CH and DH (Figure 4). For the last third of the record, since 1974, this means that groundwater drought months are now almost as likely to coincide with hot months as they are to coincide with months of precipitation drought. So the increase in the percentage of groundwater drought months that coincide with both hot months and precipitation drought months between the first and last periods of the observational record, from about 8% to 23% and from 10% to 30% for CH and DH, is almost entirely due to the effect of warming.

Although dry months (SPI ≤ 0) appear to be a broad prerequisite for groundwater drought months throughout the record at both sites (Figure 4), an increasing number of wet months are associated with groundwater drought months. For example, in the last third of the record, a total of 10 and 11 groundwater drought months at CH and DH, respectively, were associated with wet months, compared with just one month at both sites during the first third of the record up until 1932.

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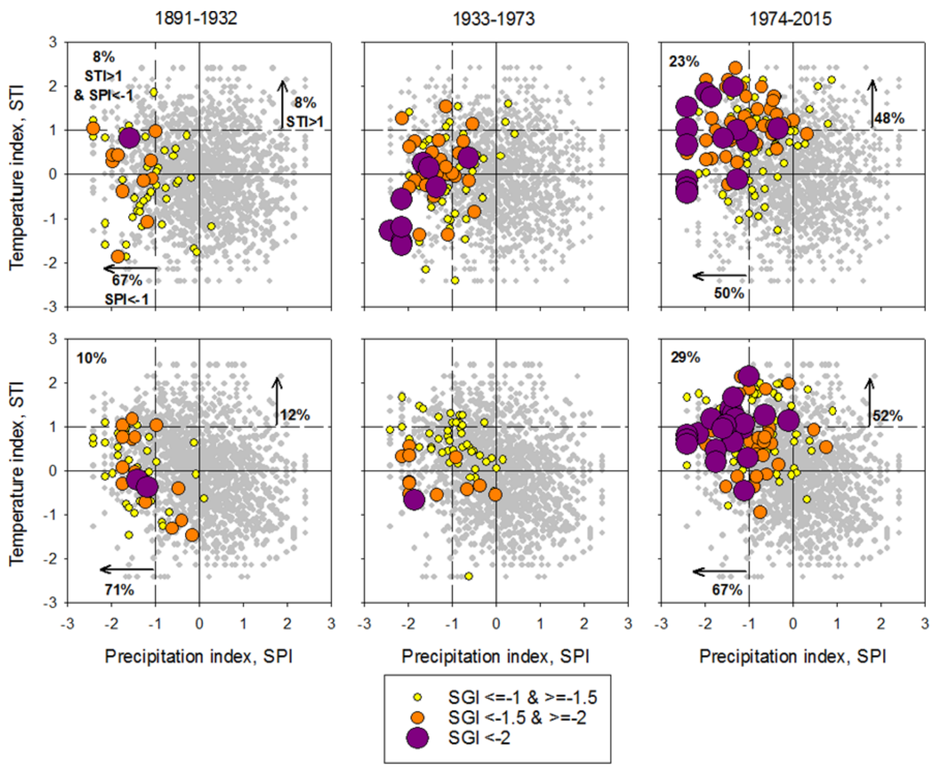

Figure 4. Changes in the incidence and magnitude of groundwater drought months since 1891 as a function of temperature and precipitation indices. Occurrence of groundwater drought months as a function of SPI and STI at CH (upper panels) and at DH (lower panels), for the periods 1890-1932, 1933-1973 and 1974-2015 (for reference, all monthly values from 1891-2015 are shown as grey symbols). Months with SGI between -1 and -1.5, yellow symbols; between -1.5 and -2, orange symbols; and <-2, purple symbols. Percentages (rounded to the nearest integer) in the top left show the proportion of months in each period where STI is ≥ 1 and SPI is ≤ -1, in the top right where STI is ≥ 1 and in the bottom left where SPI is ≤ -1.

3.3 Changes in episodes of groundwater drought

There have been 45 episodes of groundwater drought at CH and 33 at DH between 1891 and 2015. Of these, 16 episodes at CH and 8 episodes at DH had an average SGI intensity of ≤ -1 (Supplementary Information, Table S3). Across the observational record, groundwater droughts are more frequent but typically shorter and less intense at CH compared with DH (Figure 5). This is consistent with previous observations that the CH hydrograph has a shorter autocorrelation than that of DH, inferred to be due to differences in aquifer and catchment characteristics between the sites (Bloomfield and Marchant, 2013).

There is evidence for systematic changes in the occurrence and nature of episodes of groundwater drought at both sites (Figures 5 and 6 and Supplementary Information, Table S3). There has been an increase in the frequency of groundwater droughts, particularly droughts with a mean SGI of ≤ -1, duration of droughts, and an increase in the intensity of groundwater droughts. Overall, between the first and last third of the record, the number of groundwater droughts has increased from 12 to 19 and from 9 to 16 at CH and DH respectively. Over the same periods, the number of groundwater droughts with a mean of SGI of ≤ -1 has increased from 2 to 9 and from 2 to 4 events at CH and DH. Figure 6, cumulative frequency-duration plots for groundwater droughts at CH and DH for the periods 1891-32 and for 1974-2015, shows that there has been a systematic increase in the duration of the episodes of groundwater drought. At the same time as there has been an increase in frequency and duration of groundwater droughts, there has also been a systematic increase in the average intensity of those droughts (as measured by the mean event SGI) between the first and last third of the records, from -0.71 to -1.0 and from -1.2 to -1.51 at CH and DH respectively (Figure 5). All these changes in groundwater droughts are associated with a very large increase in temperature anomalies during the groundwater drought events, with average STI during episodes of groundwater drought increasing from -0.26 to 0.67 and from -0.27 to 0.60 at CH and DH. However, the increases in groundwater drought frequency, duration and intensity between the first and last third of the records are not associated with any increases in precipitation deficits (i.e. lowered SPI during episodes of groundwater drought). Instead, they are actually associated with a small rise in event average SPI during episodes of groundwater drought, from -0.72 to -0.64 and from -0.9 to -0.55 at CH and DH respectively.

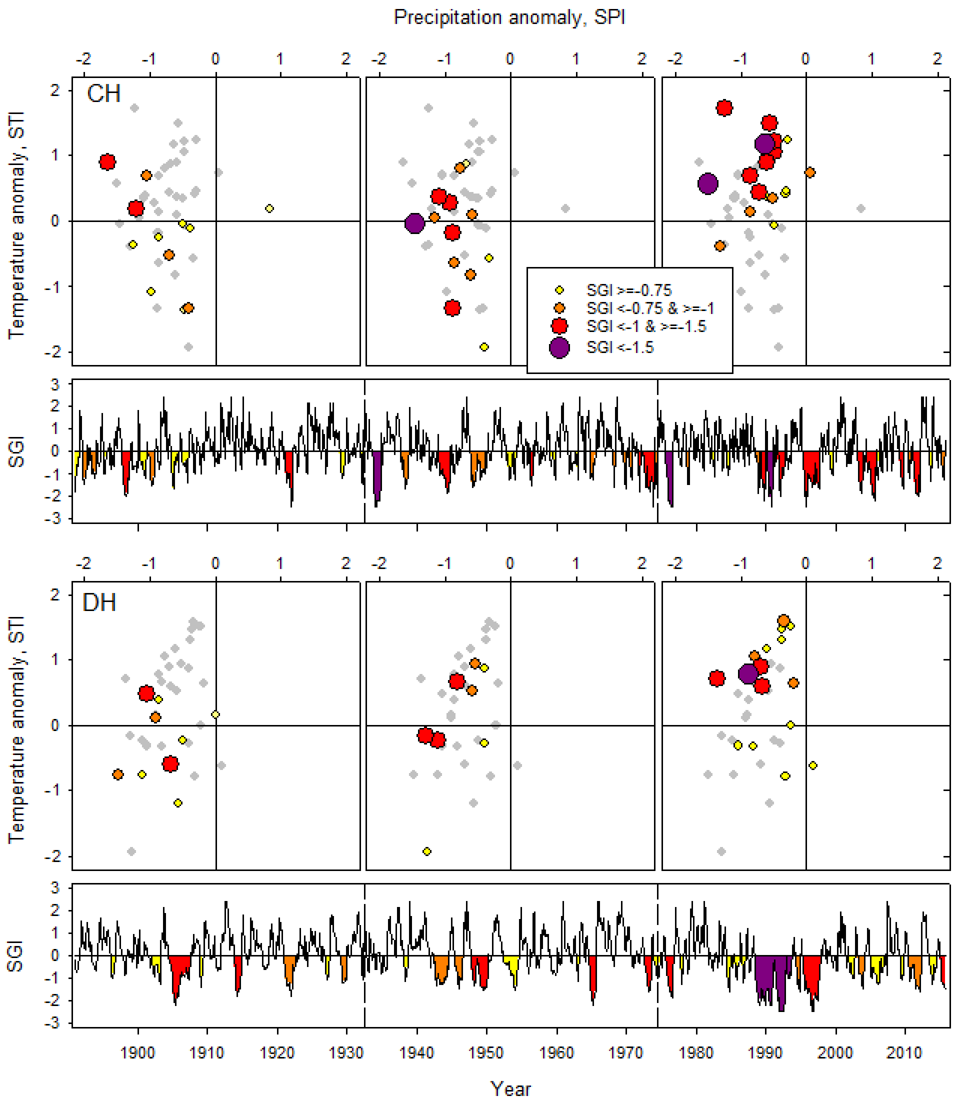

Figure 5. Changes in the incidence and magnitude of episodes of groundwater drought since 1891 as a function of temperature and precipitation. Mean groundwater drought event intensity (mean SGI) as a function of mean event SPI and STI for the periods 1891-1932, 1933-1943, and 1944-2015. Grey symbols indicate all episodes of groundwater drought at a site. Yellow through to purple symbols indicate increasing mean SGI for the episodes of groundwater drought. The SGI time series are shown below the cross plots for reference with drought events of a given magnitude highlighted in the four colours. Data for CH is shown in the upper panels and DH in the lower panels.

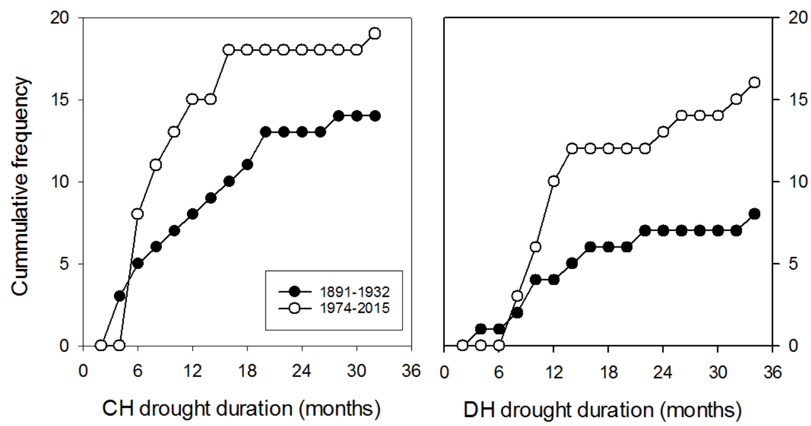

Figure 6. Cumulative frequency plots of drought duration for CH and DH for the first (closed symbols) and last (open symbols) third of the observational records.

In addition to changes in average STI and SPI during episodes of groundwater drought, there have been changes in the coincidence of episodes of groundwater drought, hot periods and precipitation droughts (Figure 7). Typically, episodes of groundwater drought coincide with precipitation droughts. However, there has been a small decline in the coincidence of groundwater and precipitation droughts across the observational record (Figure 7). For the period 1891-1932, about 83% and 78% of groundwater droughts coincided with precipitation droughts at CH and DH respectively. This fell to about 79% and 75% for the period 1974-2015. However, there has been a large increase in the coincidence of groundwater droughts with hot periods, from about 25% and 22% of groundwater droughts at CH and DH during the first third of the record, to about 74% and 63% for the last third of the record (Figure 7). Of particular note, although unusual, there have been six episodes of groundwater drought not coincident with precipitation droughts and only coincident with hot periods (three episodes at both sites), and all but one of these (an eight month episode of groundwater drought ending in October 1938 at DH) have occurred since 2002.

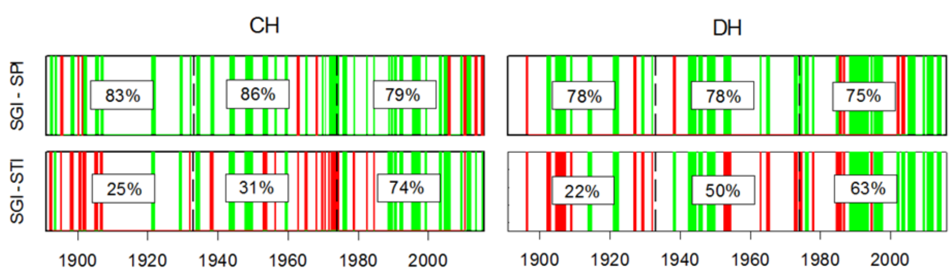

Figure 7. Coincidence of episodes of groundwater drought with precipitation droughts and with hot periods. Graphical representation of coincidence of groundwater droughts with precipitation droughts (SGI - SPI) and with hot events (SGI - STI) for CH (left panels) and DH (right panels), where green denotes coincident and red non-coincident events. Percentages (rounded to the nearest integer) indicate the fraction of coincident episodes for the first (1891-1932), middle (1933-1943) and last (1944-2015) thirds of the record (where periods are separated by vertical dashed lines).

4 Discussion and conclusions

4.1 Controls on changes in groundwater drought on the Chalk aquifer

Precipitation deficit is the primary driver of groundwater drought (Tallaksen & Van Lanen, 2004; Van Loon, 2015). This is confirmed for CH and DH where dry months (SPI ≤ 0) are a broad prerequisite for groundwater drought months throughout the record at both sites (Figure 4) and where all episodes of groundwater drought (SGI ≤ -1) are associated with negative precipitation anomalies (SPI ≤ 0) anomalies (Figure 5). However, we have also shown that there is no significant difference in the probability of precipitation drought between the beginning and end of the records at CH and DH (section 3.1) and that increases in groundwater drought frequency, duration and intensity between the first and last third of the records are not associated with any increases in precipitation deficits, i.e. lowered SPI during episodes of groundwater drought (section 3.3). Given these observations, and in the absence of major long-term changes in land cover and the absence of systematic effects of abstraction in the catchments (section 2.1), what are the controls on the observed changes in groundwater drought since 1891 at CH and DH?

Marsh et al (2007) and Marsh (2007) have previously noted that major hydrological droughts in the UK persist for at least a year, often substantially longer – a common feature of major groundwater droughts globally (Tallaksen & Van Lanen, 2004; Van Loon, 2015). This is confirmed for CH and DH (Figure 6) with the majority of the groundwater droughts at both sites having durations typically well-over 12 months. Marsh et al (2007) also noted that major hydrological droughts in the UK are almost always associated with more than one consecutive dry winter. However, there is no evidence for an increase in the frequency of consecutive dry winters either at CH or at DH. If a dry winter is defined as below average mean monthly SPI for the winter half year (September to February), there has been no systematic change in the frequency of episodes of consecutive dry winters at either site. At CH there have been 5, 6 and 6 episodes of consecutive dry winters over the periods 1891-1932; 1933-1973; and 1974-2015 respectively. Similarly, at DH there have been 5, 6 and 6 episodes of consecutive dry winters over the same periods. In addition, there appears to be no strong, systematic drying trend associated with the consecutive dry winters when they do occur. For example, the mean SPI for episodes of consecutive dry winters at CH is -0.57; -0.63; and -0.63 for the periods 1891-1932; 1933-1973; and 1974-2015, while the corresponding mean SPI for consecutive dry winters at DH it is -0.49; -0.42; and -0.69. Since there is no clear driver for change in the nature of groundwater drought at CH and DH related to precipitation deficits, and given the that there is a significant increase in air temperature associated with anthropogenic warming across the observational record at the two sites, we postulate that increased evapotranspiration (ET) associated with anthropogenic warming is a major contributing factor to the observed increasing occurrence of individual months of groundwater drought as well increasing the frequency, duration and intensity of episodes of groundwater drought.

In shallow, unconfined groundwater systems ET contributes to the formation and propagation of groundwater droughts (Tallaksen & Van Lanen, 2004; Van Lanen et al., 2013; Van Loon, 2015). Maxwell and Condon (2016) have shown how the partitioning of ET between bare soil evaporation (E) and plant transpiration (T) is controlled by depth to the water table. Based on analysis of data from shallow North American aquifers. They identified a transition from a groundwater table depth where T is groundwater dependent and E is water limited to groundwater table depth where both E and T are water limited (i.e. where groundwater is effectively

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disconnected from the land surface resulting in relatively low T and E that are limited by precipitation) at groundwater depths of the order of 5 m below ground level. Given the modelled results of Maxwell and Condon (2016), ET should have a limited effect on groundwater drought formation and propagation at CH and DH because the depth to groundwater at CH and DH associated with episodes of groundwater drought is typically in the range 35 to 45 m and 10 to 15 m below ground level respectively. The Chalk, however, is a dual porosity-dual permeability aquifer with a thick capillary fringe. Due to the micro-porous nature of the matrix it remains saturated to at least 30 m above the water table (Price et al., 1993; Ireson, 2009). Consequently, in the Chalk ET may be expected to contribute to the formation and propagation of groundwater droughts at sites with water tables at least down to 30 m below ground level and so groundwater drought formation and development may be particularly sensitive to the effects of changes in ET, and hence to anthropogenic warming.

4.2 Implications for the changing susceptibility to global groundwater droughts

Given that the sites analysed here are representative of groundwater systems in temperate hydrogeological settings, we infer that anthropogenic warming may potentially be modifying the frequency, duration and intensity of groundwater droughts globally wherever shallow, unconfined aquifers are present in temperate environments. If groundwater droughts are changing in their character due to anthropogenic warming and that these changes are mediated by ET dominated by plant transpiration (Maxwell and Condon (2016), how important might this phenomena be globally?

The partitioning of ET into plant transpiration, interception, soil and surface water evaporation at the continental to global scale is challenging, however, Good et al. (2015) have estimated that the majority of ET, about 64%, is due to plant transpiration. At the global scale, there is currently limited understanding how plants use groundwater for evapotranspiration. In the first such global analysis, Koirala et al., (2017) modelled the spatial distribution of primary production and groundwater depth and found positive and negative correlations dependent on both climate class and vegetation type. Positive correlations, i.e. higher plant productivity associated with high (shallower) groundwater tables, were generally found under dry or temperate climate class conditions, whereas negative correlations were associated with high plant productivity but with lower (deeper) water tables predominately in humid environments. When just the temperate climate class was considered, grass, crop, and shrub vegetation types (similar to those found at CH and DH) were all associated with positive correlations between vegetative production and groundwater level, with only forests showing negative correlations. Fan et al. (2013) produced the first high resolution global model depth to groundwater level depth, and, based on a conservative estimate of the maximum rooting depths of plants of 3 m below ground level, estimated that up to 32% of the global ground surface area has a water table depth or capillary fringe within rooting depth. Based on the observations above, it is clear that globally shallow groundwater systems are common, that in temperate environments shallow groundwater contributes to ET mediated by plant transpiration, and as such may be an important process effecting groundwater drought formation and propagation, and hence may be susceptible to changes due to anthropogenic warming. If the effect of future anthropogenic warming on groundwater droughts and more generally ET process in areas of shallow groundwater are to be modelled with any fidelity, there is clearly a need for a focus on improvements in modelling ET processes in shallow groundwater systems (Doble and Crosbie (2017).

4.3 Conclusions

- In the fifth IPCC Assessment of Impacts, Adaptation, and Vulnerability it was noted that 'there is no evidence that … groundwater drought frequency has changed over the last few decades' (Jiménez Cisneros et al., 2014, p.232). Here we provide the first evidence for an increase in groundwater drought frequency, duration and intensity associated with anthropogenic warming. This has been possible due to the unusually long and continuous nature of the groundwater level time series and supporting meteorological data that is available for the CH and DH sites.

- The observed increase in groundwater drought frequency, duration and intensity at CH and DH associated with anthropogenic warming is inferred to be due to enhanced evapotranspiration (ET). This is facilitated by the thick capillary fringe in the Chalk aquifer which may enable ET to be supported by groundwater through major episodes of groundwater drought.

- By extrapolation, as shallow groundwater systems are common and since in temperate environments shallow groundwater contributes to ET mediated by plant transpiration this may be a globally important process effecting groundwater drought formation and propagation. Wherever droughts in shallow groundwater systems are influenced by ET it is inferred that they may be susceptible to changes due to anthropogenic warming.

5. Author contributions

J.P.B. conceived and coordinated the project. A.A.M. prepared the SGI, SPI and STI data for analysis. B.P.M. performed statistical analyses. J.P.B. wrote the paper with input from A.A.M. and B.P.M.

6. Competing interests

The authors declare that they have no conflict of interest.

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