Asymmetric impact of groundwater use on groundwater droughts

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Abstract. Groundwater use affects groundwater storage continuously, as the removal of water changes both short-term and long-term groundwater level variation. This has implications for groundwater droughts, i.e. a below-normal groundwater level. The impact of groundwater use on groundwater droughts, however, remains unknown. Hence, the aim of this study is to investigate the impact of groundwater use on groundwater droughts in the absence of actual abstraction data adopting a methodological framework that consists of two approaches. The first approach compared groundwater droughts at monitoring sites that are potentially influenced by abstraction to groundwater droughts at sites that are known to be near-natural. Observed groundwater droughts were compared in terms of drought occurrence, magnitude, and duration. The second approach investigated long-term trends in groundwater levels in all monitoring wells. This framework was applied to a case study of the UK using four regional water management units, in which groundwater is monitored and abstractions are licensed. Results show two, asymmetric, responses in groundwater drought characteristics due to groundwater use. The first response is an increase of shorter drought events, and is found in three water management units where long-term annual average groundwater abstractions are smaller than recharge. The second response, seen in one water management unit where groundwater abstractions temporarily exceeded recharge, is a lengthening and intensification of groundwater droughts. Analysis of long-term (1984-2014) trends in groundwater levels shows mixed, but generally positive trends, while trends in precipitation and potential evapotranspiration are not significant. The generally rising groundwater levels are consistent with changes in water use regulations and with an overall reduction in abstractions during the period of investigation. We summarised our results in a conceptual typology that illustrates the asymmetric impact of groundwater use on groundwater drought occurrence, duration, and magnitude. The long-term balance between groundwater abstraction and recharge plays an important role in this asymmetric impact, which highlights the relation between long-term and short-term sustainable groundwater use.

1 Introduction

Groundwater is an essential source of water supply, as it provides almost half the global population with domestic water (Gun, 2012), 43% of the irrigation water (Siebert et al., 2010), and 27% of industrial water use (Döll et al., 2012), as well as sustaining ecologically important rivers and wetlands (de Graaf et al., 2019). The usage and dependency on groundwater resources has grown in the past decades (Famiglietti, 2014), particularly during meteorological droughts, when groundwater is used frequently (Taylor et al., 2013; AghaKouchak, 2015).

Meteorological droughts propagate through the hydrological cycle, ultimately resulting in a groundwater drought (Wilhite, 2000; Van Lanen, 2006), defined as below-normal groundwater levels that are associated with short-term reductions in storage (Chang and Teoh, 1995; Tallaksen and Van Lanen, 2004; Mishra and Singh, 2010). Increased use of groundwater before or during meteorological droughts can also lower groundwater levels and thereby aggravate groundwater droughts (Wada et al., 2013; Christian-Smith et al., 2015). Managing groundwater use during droughts is therefore important, as overexploitation of groundwater has disastrous consequences (Custodio, 2002; Famiglietti, 2014; Russo and Lall, 2017; Mustafa et al., 2017). However, to date groundwater droughts have been studied under primarily near-natural conditions and there is limited conceptual understanding of the impact of groundwater use on groundwater droughts despite this being of interest to water regulators and policy makers.

Under near-natural conditions, the propagation of meteorological droughts to groundwater droughts depends on the antecedent condition of the land surface, subsurface controls on recharge, and non-linear response of groundwater systems (Eltahir and Yeh, 1999; Peters et al., 2006; Tallaksen et al., 2009). These processes determine the spatial distribution, duration, magnitude, and recovery of near-natural groundwater droughts (Van Lanen et al., 2013; Van Loon, 2015; Parry et al., 2018). However, in human-modified environments, groundwater droughts are also impacted or driven by water use (Van Loon et al., 2016b). This type of groundwater drought is therefore distinguished from a natural drought and referred to as human-modified or human-induced drought (Van Loon et al., 2016a).

In human-modified environments, understanding the influence of groundwater use on groundwater drought requires information related to the natural propagation of a drought and groundwater use in time. Droughts are influenced by historical and recent abstractions, as these change both short-term and long-term groundwater storage (Gleeson and Richter, 2017; Thomas and Famiglietti, 2015; Jackson et al., 2015). Unfortunately, information on groundwater abstraction, if available at all, is often considered commercially confidential. Abstraction records are usually unavailable for research, although these records are included in groundwater models developed for commercial and regulatory purposes (Shepley et al., 2012). Consequently, qualitative information about groundwater use and management regulations is invaluable to investigate the influence of groundwater abstraction on groundwater droughts (Döll et al., 2014; Panda et al., 2007). Management regulations are organised on regional or even national scale. This scale differs from the much smaller scale at which groundwater droughts are often studied. For example, physically-based groundwater models, which are developed for regulatory purposes or research, rarely cover the entire drought-impacted area or the entire aquifer that is affected by a drought event (Peters et al., 2006; Tallaksen et al., 2009; Shepley et al., 2012). Studying groundwater droughts in human-modified environments would thus require a regional approach to align the scale of a groundwater drought study with the scale at which management decisions are made.

The aim of this study is to investigate impact of groundwater use on regional groundwater droughts in the absence of actual abstraction data. For doing so, a methodological framework is designed to investigate groundwater droughts in water management units under a broad range of conditions, i.e. from where groundwater use is a small proportion of the long-term annual average recharge to where it is a significant proportion of the long-term annual average recharge. A case study from the United Kingdom (UK) is used consisting of four water management units over two main aquifers in the UK. As is common elsewhere, no data is freely available on actual abstractions in the case study area. However, information indicating the annual maximum

abstraction according to the groundwater abstraction licences is available and groundwater level observations are provided for 170 sites in the four water management units. Consequently, inferential approaches are used to assess the impact of abstraction on groundwater droughts. Here, we used two complementary approaches. Firstly, given the typically good correlation between precipitation and groundwater level time series under near-natural conditions (Bloomfield and Marchant, 2013; Bloomfield et al., 2015; Kumar et al., 2016), we used correlations defined by a limited number of near-natural groundwater hydrographs as reference. Deviations from this reference correlation are then used to qualitatively subdivide sites in on average uninfluenced and influenced by abstraction. This subdivision is used to characterise the impact of groundwater abstraction on regional groundwater droughts. Secondly, long-term abstraction influence is investigated through the spatial distribution of trends in groundwater level time series in relation to the distribution of licensed abstractions. Results are discussed in terms of the role groundwater abstraction plays in modifying near-natural groundwater droughts. A conceptual figure is proposed suggesting that long-term groundwater abstraction may modify drought frequency, duration, and magnitude depending on the proportion of abstraction and recharge.

2 Study area

The UK case study consists of four water management units (1: Lincolnshire, 2: Chilterns, 3: Midlands, 4: Shropshire) across Chalk and Permo-Triassic sandstone aquifers that are the two main aquifers in the UK (Figure 1). The two aquifers have contrasting hydrogeological characteristics. Regional groundwater flow and storage in the Chalk aquifer are dominated by its primary fracture network (Bloomfield, 1996) and secondary solution-enhanced fractures (Downing et al., 1993; Maurice et al., 2006). The response of Chalk groundwater hydrographs to driving meteorology is a function of regional variations in the nature of the fracture network, extent of karstification, nature of overlying superficial deposits amongst other factors (Allen et al., 1997). In the Permo-Triassic sandstone aquifer, groundwater flow and storage are influenced by variations in the matrix porosity, aquifer thickness, and to some extend on fracture characteristics (Shepley et al., 2008; Allen et al., 1997). Faults divide the Permo-Triassic sandstone in separate sections and the impact on regional groundwater flow varies: some faults act as hydraulic barriers and other times enhance permeability resulting in increased recharge (Allen et al., 1997). Hydrographs in the Permo-Triassic sandstones typically respond more slowly to driving meteorology than those in the Chalk (Bloomfield and Marchant, 2013) and are influenced by local variation in aquifer thickness and confinement by superficial deposits.

Regional hydrological features of the four water management units in the aquifers are summarised in Table 1. Two of the water management units are situated in eastern England (Lincolnshire, unit 1) and central southern England (the Chilterns, unit 2) and are underlain by the Chalk aquifer, and two of the water management units are situated in central England (East Midlands, unit 3) and north west England (Shropshire, unit 4) and are underlain by the Permo-Triassic sandstone aquifer. The largest groundwater use sector in these management units is drinking water, followed by industry, agriculture and environmental water use (BGS, 2015). Groundwater use is regulated using abstraction licences, which have changed since their introduction in 1963 (Ohdedar, 2017). Since the implementation of the Water Framework Directive in 2000, abstraction licences follow a water balance approach to ensure 'good groundwater status' resulting in a reduction of licensed groundwater use (Environment

Table 1. Regional features of the four water management units summarising the area size, long-term precipitation (P) and potential evapotranspiration (PET) as calculated by Mansour and Hughes (2018) based on daily data from 1962 to 2016, hydrogeological features and main groundwater use changes in time. All water management units are shown in Figure 1. In Figure S1, the purpose and locations of recent abstraction licences are shown. Hydrogeological information and groundwater use is based on Allen et al. (1997) and complemented with additional references (see last column).

Water management unit & number of monitoring wells	Area (km²)	Annual average (mm/yr)	Hydrogeological features	Groundwater use	Additional literature
1: Lincolnshire 38 wells	1310	P: 589 PET: 454	Highly permeable outcrop due to dissolved fractures and weathering South-East of aquifer increasingly confined by superficial deposits	Abstraction peaked in 1970 and reduced since 2000 Abstractions exceed average recharge only during droughts	Whitehead and Lawrence (2006) Bloomfield et al. (1995), Hutchinson et al. (2012)
2: Chilterns 45 wells	1650	P: 674 PET: 485	Chalk aquifer partly covered by superficial deposits karstification in valleys	Abstractions increased during 1970-2003 and decreased after 2003 recent abstraction is estimated on 50% of average recharge	Jones (1980), Jackson et al. (2011) Environment Agency (2010)
3: Midlands 36 wells	1100	P: 630 PET: 476	Varying aquifer thickness from 120-300m Confined by superficial deposits in the East	Abstraction exceeded the average recharge rates by 25% in 1980-90 Abstraction reduced in 2000 to meet average recharge	Zhang and Hiscock (2010) Shepley et al. (2008)
4: Shropshire 51 wells	1400	P: 722 PET: 471	Highly variable aquifer thickness: 30-1400m Major faults interrupt groundwater flow across sandstone layers	Abstraction represented 40-50% of recharge in 1970-90 and reduced after 2000. River augmentation scheme increases abstractions during dry periods	Cuthbert (2009), Voyce (2008) Shepley and Streetly (2007)

Agency, 2016). Specific information regarding the change in water use in these water management units was found in previous
95 groundwater studies (see fifth column of Table 1).

3 Data and Methods

3.1 Data

The analysis has been undertaken for a 30-year period (1984-2014) using precipitation, evapotranspiration, and groundwater level time series. This time period includes at least four major droughts with national spatial extent, namely: 1988-1994,
100 1995-1997, 2003-2006, and 2010-2012 (Durant, 2015).

Precipitation and potential evapotranspiration data were obtained from the GEAR dataset (Tanguy et al., 2016) and the CHESS dataset (Robinson et al., 2016). The gridded (1 km²) GEAR dataset contains interpolated monthly precipitation estimates derived from the UK rain gauge network. The CHESS dataset is also gridded (1 km²) and contains climate data, from which potential evapotranspiration estimates are computed using the Penman-Monteith equation. We aggregated daily poten-
105 tial evapotranspiration estimates to monthly sums. For both gridded datasets (GEAR and CHESS) grid cells were extracted corresponding to groundwater well locations. The 1 km² gridded precipitation and potential evapotranspiration sums were compared to monthly groundwater observations of the same location. This point-scale comparison assumes that the influence of precipitation is largest surrounding a groundwater monitoring site (Bloomfield and Marchant, 2013; Bloomfield et al., 2015; Li and Rodell, 2015; Kumar et al., 2016).
110 Precipitation estimates were converted into standardised precipitation indices (SPI) following the method of McKee et al. (1993). A gamma distribution was fitted to precipitation estimates and alternative distributions were also tested (Normal, Pearson III, and Logistic). Considering the use of SPI to account for delayed recharge, a large range of accumulation periods of precipitation (1 to 100 months) was calculated in order to find the optimal correlations between precipitation and groundwater

time series. For this particular use of the SPI, the 'best' fitting distribution varies (Svensson et al., 2017). Alternative distributions showed minimal differences in the computed correlations between standardised precipitation and groundwater time series, hence we decided therefore to use the gamma distribution.

Groundwater level time series were obtained from the national groundwater database in the UK, which contains time series for both reference wells and (regular) monitoring wells. 209 sites have been included in the analysis, of which 39 are reference sites and 170 (regular) monitoring sites. Reference sites were taken to represent near-natural conditions in the 30-year time period. These sites were selected from the Index and Observation wells listed in the UK Hydrometric Register (Marsh and Hannaford, 2008) and have previously been assessed by the British Geological Survey. Well descriptions indicate near-natural or possible (intermittent) influence of groundwater abstraction. Wells selected for this study are categorised as near-natural reflecting regional variation in groundwater levels with minimal abstraction impacts. This selection of reference wells includes 30 wells in the Chalk and 9 wells in the Permo-Triassic sandstone. Regular monitoring sites are part of the monitoring network in place in the four water management units. Initially, 660 monitoring sites were originally considered for the regional groundwater drought analysis that were truncated to the 30-year analysis period and quality checked. Unrealistic observations were cross-validated with available meta-data, and if unexplained, removed from the dataset. Missing data were linearly interpolated from the last observation to the next observation in case of short sequences of missing data (less than 6 months) (Tallaksen and Van Lanen, 2004; Thomas et al., 2016). Sites with records containing longer sequences of missing data were removed from the dataset prior to the analysis leaving a total of 170 (out of the original 660) groundwater level time series that were deemed of good quality, of which 38 were located in Lincolnshire, 45 in Chilterns, 36 in Midlands, and 51 in Shropshire.

All groundwater level time series were standardised into the Standardised Groundwater level Index (SGI) (Bloomfield and Marchant, 2013), which is briefly explained here. Monthly groundwater observations were grouped for each calendar month and within each month observations were ranked and assigned a SGI value based on an inverse normal cumulative distribution of the data. No distribution was fitted, but SGI values were assigned to monthly observations accounting for seasonal variation within the calendar year. The resulting SGI time series represent extremely low to below-normal ($-3 < SGI < 0$) and above-normal to extremely high ($0 > SGI > 3$) monthly groundwater levels in the groundwater time series. Groundwater level observations are physically constrained by length of the screened interval of the borehole. Therefore, the lowest SGI value might indicate that groundwater levels fell below the borehole screen and highest SGI value can indicate groundwater levels reached the surface.

Qualitative information about groundwater use was provided for each water management unit by the national regulator (the Environment Agency (EA) in England). Detailed maps were made available regarding the purpose and recent (dated at 2015) licensed abstraction volumes (see Figure S1). In addition, reports describing the EA's regional groundwater resource models and location specific groundwater studies were used as reference material to indicate changes in groundwater use (Table 1).

3.2 Methods

The developed methodological framework consists of two approaches to investigate the impact of groundwater use on groundwater droughts. The first approach uses a regional near-natural groundwater drought reference based on the reference wells.

SGI time series of reference wells are clustered to identify common spatial and temporal patterns in near-natural groundwater levels of the two aquifers. Reference wells were taken to represent regional groundwater variation that is primarily driven by climate and hydrogeology. Then, monitoring wells in each of the four water management units were paired to these regionally-coincident clusters of reference wells (Figure 1). The occurrence and characteristics of droughts in monitoring wells were compared with those in paired reference clusters to assess potential effects of abstraction on groundwater droughts. The second approach consisted of a groundwater trend test that quantified long-term trends as a consequence of continuous impact of groundwater use in the water management units. The spatial distribution of identified trends was evaluated according to annual abstraction licences in the water management units.

3.2.1 Time series clustering

Three hierarchical clustering methods: single linkage, complete linkage, and Ward's minimum were tested to find the most suitable and least biased approach for clustering SGI time series of the reference wells (Haaf and Barthel, 2018). In each method, Euclidean distance was used as measure of similarity and cluster compositions that showed the least overlap between clusters were selected (Aghabozorgi et al., 2015). Criteria for the clusters were set by previous studies (Chalk aquifer only) and known hydrogeological differences in the aquifers. For both aquifers, the minimum number of hydrograph clusters was sought that produced spatially-coherent clusters.

3.2.2 Correlation between SPI$_Q$-SGI

Under near-natural conditions, the optimum correlation between standardised precipitation and groundwater indices (SPI$_Q$-SGI) is generally high in unconfined aquifers (Bloomfield and Marchant, 2013). Anomalies in precipitation propagate with a relatively constant delay in recharge to the groundwater, which is due to, subsurface controls on recharge, the antecedent condition of the land surface, and non-linear response of groundwater systems (Eltahir and Yeh, 1999; Peters et al., 2006; Tallaksen et al., 2009). This constant delay is included by the optimal precipitation accumulation period in the calculated SPI$_Q$-SGI correlation represents a long-term relationship for a certain site, as both the SPI and SGI were calculated for a continuous 30-year period including all seasons and both anomalously dry and wet periods.

The SPI$_Q$-SGI correlation can be reduced when groundwater level response becomes disconnected from driving precipitation under confined conditions (Bloomfield et al., 2015; Kumar et al., 2016; Lee et al., 2018) or when groundwater abstraction changes groundwater storage and levels independent from driving precipitation (Bloomfield et al., 2015; Lorenzo-Lacruz et al., 2017; Haas and Birk, 2017). In this study, the impact of confined conditions on reducing the SPI$_Q$-SGI correlations is expected to be minimal, as only a small selection of Chalk sites are located in the semi-confined Chalk in South Lincolnshire (Table 1). On the other hand, the impact of dynamic groundwater use on SPI$_Q$-SGI correlations is expected to be significant, as long-term changes in groundwater use in the water management units resulted in a spatially heterogeneous pattern of irregular, decreasing, or increasing influence of abstraction on groundwater storage. For example, Ohdedar (2017) shows that groundwater use in the UK increased until the late 1980s and reduced afterwards with a large redistribution of where water is taken from to minimise the impacts on low flows.

The presence or absence of human-influence on groundwater observations in the water management units was determined on the basis of the SPI_Q-SGI in each near-natural reference cluster. For each cluster, the lowest SPI_Q-SGI correlation was used as a threshold to differentiate long-term *influenced* from *uninfluenced* groundwater monitoring sites. Monitoring wells with high or higher SPI_Q-SGI correlations are regarded as (on average over the 30-year investigation period) uninfluenced and those with lower correlations as potentially human-influenced. An illustrated example is provided in Figure S2 showing SGI time series of a near-natural reference site and three groundwater monitoring sites. Statistical differences between the categorised uninfluenced and influenced wells were computed using a non-parametric Wilcox test.

3.2.3 Drought analysis

Groundwater droughts were defined using a threshold approach applied to the SGI series. Groundwater droughts are considered to occur when the SGI value is at or below -0.84, which corresponds to a 80th percentile or a 'once every 5 year drought event' (Yevjevich, 1967; Tallaksen and Van Lanen, 2004; Tallaksen et al., 2009). Drought characteristics were compared between reference clusters and monitoring sites focusing on drought occurrence, frequency, duration, and magnitude.

3.2.4 Trend test

The second approach consisted of a monotonic trend test applied to all monitoring sites given the previously identified trends in human-modified groundwater systems (Thomas and Famiglietti, 2015; Sadri et al., 2016; Bhanja et al., 2017; Pathak and Dodamani, 2018). This trend test contributes to the first approach, as the SGI and SPI_Q-SGI correlation analysis do not specifically account for trends in groundwater time series that could result in significant trends going unnoticed. Hence, an additional trend test was introduced to compare trends in annual (averaged for each calendar year) groundwater levels to climate data (precipitation and evapotranspiration) that were extracted for grid cells corresponding to groundwater well locations from the GEAR and CHESS datasets (Tanguy et al., 2016; Robinson et al., 2016).

Trends were quantified by the trend Z value showing positive or negative deviations from the null hypothesis (no trend). Positive/negative Z values indicated increasing/decreasing trend directions. $|Z|$ values over $|2.56|$ (α = 0.01) were considered significant. Trends in groundwater level time series were tested using a modified Mann-Kendall trend test (Mann, 1945; Kendall, 1948), which includes a modification developed by Yue and Wang (2004) to account for significant auto-correlation in the annual groundwater data (Hamed, 2008). Trends in climate time series were also calculated from annual data using a standard Mann-Kendall trend test.

4 Results

4.1 Near-natural groundwater reference clusters

The near-natural groundwater reference clusters, based on SGI clusters of the reference wells and the clustering criteria, were defined by Ward's minimum clustering technique. The Ward's minimum cluster composition shows the least overlap between

clusters of the three tested clustering techniques (Figure S3). Eight clusters are identified, of which five clusters are located in the Chalk (C1-5) and three in the Permo-Triassic Sandstone (S1-3) (Figure 1). The spatial distribution of Chalk clusters (C1, C3, C4) is consistent with clusters identified by Marchant and Bloomfield (2018). Two additional clusters are identified, of which one is located in East Anglia (5 reference wells in C2) and one in South East England (2 wells in C5). The cluster dendrogram shows a small difference in similarity between C4 and C5, which is located close to the coastline (cluster dendrogram result not shown; difference between C4 and C5 is shown in Fig. S2). C1 and C3 are coincident with water management unit 1 and 2, and are used as near-natural reference for monitoring sites in those units. In the Permo-Triassic sandstone aquifer, only one spatially coherent cluster (S2) is found when all nine SGI time series are clustered (Figure 1). The cluster composition of the other two smaller clusters (S1 and S3) is not spatially coherent and there is no evidence of previous clustering studies available that can confirm these two clusters. Hence, only S2 is used as near-natural reference for monitoring sites in water management units 3 and 4.

The optimal SPI_Q-SGI correlations of near-natural wells are high on average (0.79) with a range of 0.66 to 0.89. These correlations are found using the optimal accumulation period, which accounts for delay in recharge that is different for each reference cluster. High SPI_Q-SGI correlations are found for both short and long accumulation periods and there was no systematic relationship between the SPI_Q-SGI correlation and the SPI accumulation period Q or SGI autocorrelation in the near-natural wells. C1 represents a relatively fast-responding section of the Chalk and has a short Q of 12.6 ± 5.4 months. The Q of C2 and C3 is higher, respectively 18.2 ± 4.3 and 24 ± 8.6 months. This corresponds to the delay in groundwater recharge due to the Quaternary deposits present in these regions (Allen et al., 1997). In the South East, the Chalk is highly fractured, which is reflected by a short Q of 8 ± 2.2 months for C4 and C5. In the Permo-Triassic sandstone, the Q of S2 is 35 ± 4.5 months, which confirms a slow-responding groundwater system (Allen et al., 1997).

In the monitoring sites, the majority of the SPI_Q-SGI correlations are as high or higher than the minimum correlation of paired reference clusters. Hence, these monitoring sites are considered, on average, uninfluenced by abstraction. The percentage of uninfluenced sites varies between the water management units. The largest percentage is found in the Chilterns (71%), followed by the Midlands (63%), Shropshire (53%), and Lincolnshire (31%). Monitoring sites with a SPI_Q-SGI correlation below the minimum correlation of the paired reference cluster are treated as possibly influenced by abstraction.

The found optimal precipitation accumulation periods within the management units is variable and appears to be in part a function of aquifer depth and the local nature of aquifer confinement (Figure S4). For example, shorter accumulation periods are found in shallow sections of the aquifer (East Shropshire and West Chilterns), and in outcrops (East Lincolnshire). Longer accumulation periods are found in deep sections of the Permo-Triassic aquifer (West Shropshire) and semi-confined sections of the Permo-Triassic (Midlands) and Chalk aquifer (East Chilterns, and South East Lincolnshire).

4.2 Groundwater droughts

Groundwater droughts observed in the reference clusters reflect both spatial and temporal variation due driving precipitation and hydrogeology setting. In general, the four UK-wide droughts (1988-1993, 1995-1998, 2003-2006, and 2010-2012) are reflected in near-natural groundwater time series. Spatial patterns in driving precipitation, however, result in variable ground-
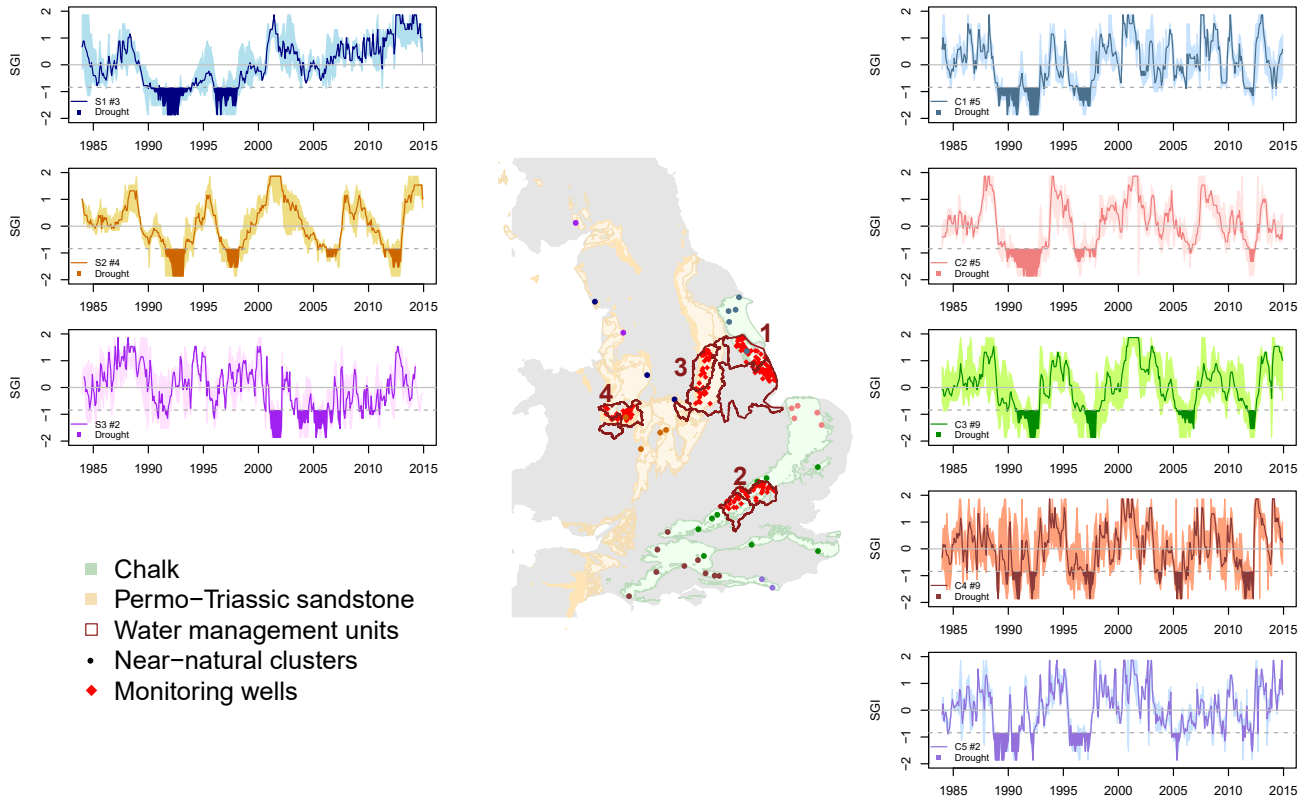
Figure 1. Eight clusters based on the 39 reference groundwater sites in the Permo-Triassic sandstone and Chalk aquifer are shown, representing long-term near-natural groundwater level variation. All time series are standardised for the 30-year time period (1984-2014). In the centre, locations of the reference wells are shown marked by the dots in different colours for all eight clusters. The four water management units are indicated in dark red (groundwater monitoring sites in triangles). Three of these units coincide with reference clusters: 1: Lincolnshire (C1), 2: Chilterns (C3), and 4: Shropshire (S2). S2 is also used to compare water management unit 3 (Midlands) as this is the nearest reference cluster in the Permo-Triassic sandstone. In the panels left (Permo-Triassic sandstone) and right (Chalk), SGI time series are shown for each cluster, showing the cluster mean (thick line), the range of all reference wells in the cluster (shaded coloured area) and reference droughts of the cluster mean (filled area).

Table 2. Average drought characteristics (duration, magnitude, and frequency) of all monitoring sites in the four water management units. 5th - 95th percentile of the drought characteristics are in parentheses. Distribution plots for all drought characteristics can be found in S5,S6,S7. The monitoring sites are separated using the lower limit of the cluster SPI_Q-SGI into on average *uninfluenced* and *influenced*. Differences between the two groups are tested for significance using a Wilcox test. Tests for which the p<0.05 are in **bold**.

	Uninfluenced wells (%)	Duration (in months)		Magnitude (from SGI)		Frequency	
		Uninfluenced	Influenced	Uninfluenced	Influenced	Uninfluenced	Influenced
		Average	Average	Average	Average	Average	Average
1: Lincolnshire	31	**7.6 (1 - 28)**	**3.3 (1 - 12)**	-3.4 (-19 - -0.05)	-1.5 (-6.1 - -0.05)	**11.0 (4 - 17)**	**24.9 (12 - 36)**
2: Chilterns	71	**8.67 (1 - 24)**	**3.4 (1 - 11)**	**-3.9 (-15 - -0.05)**	**-1.54 (-6.5 - -0.05)**	**10.0 (5 - 18)**	**25.4 (9 - 34)**
3: Midlands	63	9.89 (1 - 36)	11.6 (1 - 45)	-4.5 (-22 - -0.05)	-5.3 (-26 - -0.05)	**9.5 (3 - 16)**	**9.0 (4 - 20)**
4: Shropshire	53	**6.8 (1 - 24)**	**5.0 (1 - 24)**	-3.1 (-14 - -0.05)	-2.3 (-12 - -0.05)	**11.9 (5 - 17)**	**15.7 (10 - 24)**

water drought occurrence (Figure 1). For example, in C1 groundwater levels are low in 2003-06, but not below the drought threshold. In C2, groundwater levels are slightly lower and a short drought event is observed in the SGI cluster mean. In C3-5 and S2, however, the 2003-06 drought event was a major drought event. Spatial variation in the hydrogeology results in varying drought duration for the Chalk clusters. In central England, longer drought durations are found in clusters C2 and C3. This region is partly covered by Quaternary deposits that delays recharge. Shorter (and more frequent) events are observed in C4 and C5, which are located in highly fractured Chalk.

On a smaller scale in the water management units, average drought characteristics (duration in months, magnitude in accumulated SGI over the drought period, and frequency) for monitoring sites show differences due to abstraction influence, which we have classified in, on average, uninfluenced and influenced sites, see Table 2. Shorter and less intense, but more frequent drought events are observed in the influenced sites in Lincolnshire, Chilterns, and Shropshire. In these water management units, the difference in average drought duration and frequency is significant. Droughts are observed twice as often in influenced compared to uninfluenced sites in Lincolnshire and Chilterns, but this difference is smaller in Shropshire. The distribution of recorded drought frequency (Figure S5) shows that the difference between on average influenced and uninfluenced sites is less pronounced in Lincolnshire and Shropshire. Table 2 shows that the average drought duration of influenced sites exceeds the duration in uninfluenced sites in the Midlands. Longer and more intense groundwater droughts occurred less often in influenced sites, which is in contrast with the other water management units. The distribution of recorded drought frequency (Figure S5) shows a majority of sites recording fewer droughts and some sites that record a higher frequency. On average, this results in a small difference between the influenced and uninfluenced sites.

Drought characteristics in Table 2 suggest that drought events vary widely within and between water management units. These differences are shown in a combined time series plot in Figure 2 capturing reference droughts and drought recorded in monitoring sites that are colour-coded by the drought intensity. These monitoring sites are sorted based on their SPI_Q-SGI correlation (high to low). The cluster minimum SPI_Q-SGI correlation is indicated with a dashed line, i.e. 0.75 for Lincolnshire, 0.71 in the Chilterns, and 0.69 in the Midlands and Shropshire. Below this minimum correlation, drought occurrence in un-

influenced sites aligns mostly with that of droughts in the reference clusters. Categorised influenced sites (those with SPI_Q-SGI correlations lower than the cluster minimum) had typically shorter, but more drought events of a lower magnitude in Lincolnshire, Chilterns, and Shropshire. The distribution of drought duration in Figure S6 shows that the majority of these additional droughts is recorded in influenced sites compared to uninfluenced sites in Lincolnshire, Chilterns, and Shropshire. Contrastingly, longer and more intense droughts are observed in all Midland sites in 1990-95. Droughts observed in influenced sites are also longer in 1984-1986, 1997-2001, and 2005-06 compared to the reference cluster and fewer droughts are observed in 2010-12.

The additional events in influenced sites coincide with low SGI values in the reference wells that sometimes occur prior to a long drought event. For example, additional droughts are observed in 1984, 1995-96, 2005-06, and 2014 in Lincolnshire, and in 1984-86, 2004, and 2009-10 in the Chilterns. In those periods, the reference cluster mean was below 0, but not below the drought threshold. In the case of 1995-96, 2004, and 2009-10, these additional drought events occurred prior to a long drought event. However, there was no no consistency between the study areas in relation to the timing of these shorter drought events. In Lincolnshire, minor droughts occur more often during reference droughts. In the Chilterns and Shropshire, more droughts are detected prior to reference droughts (Table S8). All minor droughts are shorter than the groundwater memory (auto-correlation) suggesting that these minor droughts are less likely to be related to propagated precipitation deficits, but instead are probably related to groundwater abstraction.

Drought descriptions in the literature show an increase in water demand during the 1995-97, 2003-06 and 2010-12 drought (Walker and Smithers, 1998; Marsh et al., 2013; Durant, 2015). For example, Durant (2015) found that during the 1988-93 drought event evapotranspiration was exceptionally high. Impacts were mostly felt in the Chalk, particularly in regions where groundwater is the principal source of water supply where abstractions amplified the drought effects. An extreme rise in water use was reported by Walker and Smithers (1998) during the 1995-1997 drought event putting strain on drinking water supply systems in North East England. Sections of the Permo-Triassic sandstone were amongst the worst affected with drought conditions until 1998 (Durant, 2015). During the 2003-06 and 2010-12 droughts, a sudden increase in groundwater use was found that was attributed to dry weather and hot summers in the work of Marsh et al. (2007, 2013) and Durant (2015). In the work of Rey et al. (2017), low SPI_3 values were found in summer months for 1995, 1996, 2003-2006, and 2010-2011 highlighting exceptional dry weather that led to surface water use restrictions prior to droughts to maintain low flows. Consequently, the reduced surface water abstractions were replaced by groundwater, for which use was rarely restricted (Rey et al., 2017) resulting in lowered groundwater levels and potentially aggravating groundwater droughts.

Over the whole investigation period, drought magnitude seems to be decreasing since the 1995-1997 drought event. Droughts observed in 2003-2006 and 2010-12 are shorter and of lower magnitude than the 1995-97 drought in most sites. This is seen most convincingly in Lincolnshire, Chilterns and the Midlands, where the magnitude of droughts decreases dramatically over the 30-year time period. In Shropshire, this tendency is less strong, as the 2010-12 drought was of a similar magnitude as the 1995-1997 drought.
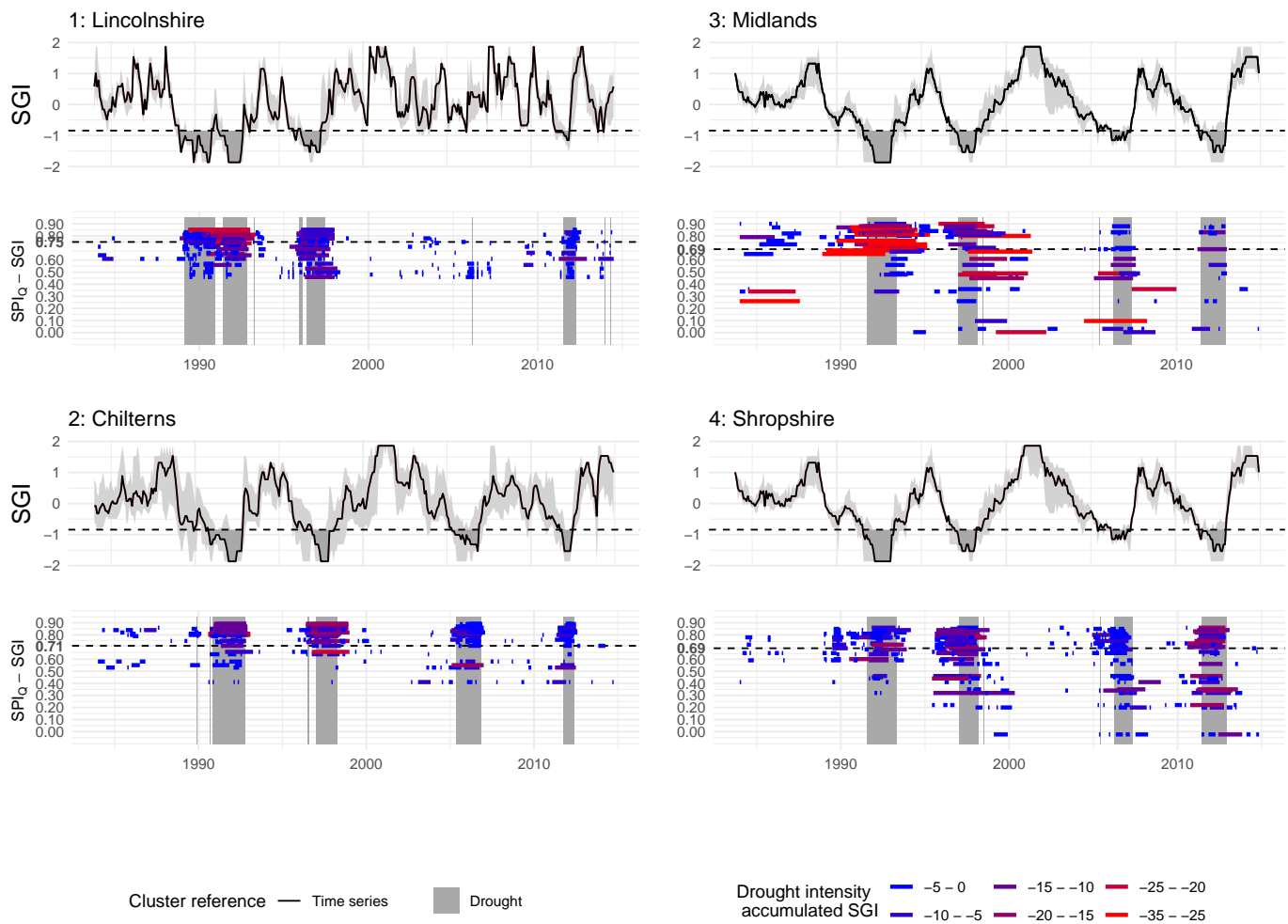
Figure 2. Drought occurrence visualised for all four water management units: 1: Lincolnshire, 2: Chilterns, 3: Midlands and 4: Shropshire. The top panel shows the SGI hydrograph of the reference cluster mean based on reference wells (see Figure 1 for the location). The range of reference clusters is coloured in grey. The dotted line represents the drought threshold for the cluster mean with shaded areas for the reference drought events. These reference drought events are also shown in long grey panels in the lower plot that shows the individual droughts as found in monitoring sites in each water management unit. The length of coloured bars indicates the drought duration and the colour represents drought magnitude of each drought in blue-red scale for accumulated SGI.

4.3 Trends in groundwater

Significant trends in groundwater level have been detected in 38% of all monitoring sites in the water management units. Of these 38%, half of the trends are upward (positive) and the other half is downward (negative) trends (Figure 3). Overall, upward trends are dominating (61% of sites including significant and non-significant trends) indicating a sustained rise in the 30-year groundwater level time series. Fewer (39% including significant and non-significant) downward trends are detected indicating sustained lowering of groundwater levels. The presence of these significant trends in groundwater is notable given the weak, non-significant, trends in the 30-year precipitation and potential evapotranspiration data (P: Z = -0.75 - 1.53, PET: Z = 0 - 0.65).

The direction of trends in groundwater and their spatial coherence within the water management units show different patterns (Figure 3). In the Chalk water management units, positive trends dominate. In Lincolnshire, 5 out of the total 25 positive trends are significant, compared to 3 out of 32 in Chilterns. There are fewer negative trends detected in both water management units, but more of these are significant, respectively 7 out of 13 in Lincolnshire and 4 out of 12 in Chilterns. In Lincolnshire, sites with a negative trend are, all but one, located in the semi-confined Chalk. This is in sharp contrast with the semi-confined Chalk in Chilterns, where mainly (significant) positive trends are found. In the Permo-Triassic sandstone water management units, more significant trends are detected compared to the Chalk (63% in Midlands and 43% in Shropshire). In the Midlands, more positive than negative trends are detected. In total, 17 out of 25 positive trends are significant, compared to 6 out of 11 significant negative trends. Negative trends are mainly found in the centre of the water management unit. Positive trends are found north and south of that. In Shropshire, more negative than positive trends are detected. 31 sites have a negative trend, of which 15 significant. These trends are mainly detected in the west of the water management unit. Positive trends are mainly located east in between two fault lines (Ollerton and Childs Ercall Fault (Voyce, 2008)). Seven of these positive trends (20 in total) are significant. In Fig. 3, the maximum licensed abstraction volumes are also shown. These licences show in which aquifer sections groundwater is primarily abstracted. However, without a record of the actual use of these licences it is impossible to directly relate detected trends to these abstraction locations.

5   Discussion

Presented results of the UK case study show that groundwater droughts in the Chalk and Permo-Triassic sandstone aquifer are primarily driven by precipitation, and modified by the hydrogeology setting and groundwater use. The precipitation gradient was the primary driver for regional variation in near-natural groundwater droughts in 1989-1992 and 2003-06, which is confirmed by the work of Bryant et al. (1994) and Marsh et al. (2007). This explains the absence of a groundwater drought in 2003-06 in the northern Chalk (C1), compared to the southern Chalk (C2-C5). Regional variation of near-natural droughts within the different hydrogeological units was linked to the hydrogeological setting, as accumulation period varied in each reference cluster. These accumulation periods align with previous findings of Bloomfield and Marchant (2013). On a smaller scale, accumulation periods varied gradually within the water management units, as a function of aquifer depth and confinement of the aquifer, which was also found by Kumar et al. (2016), Van Loon et al. (2017) and Haas and Birk (2017). The
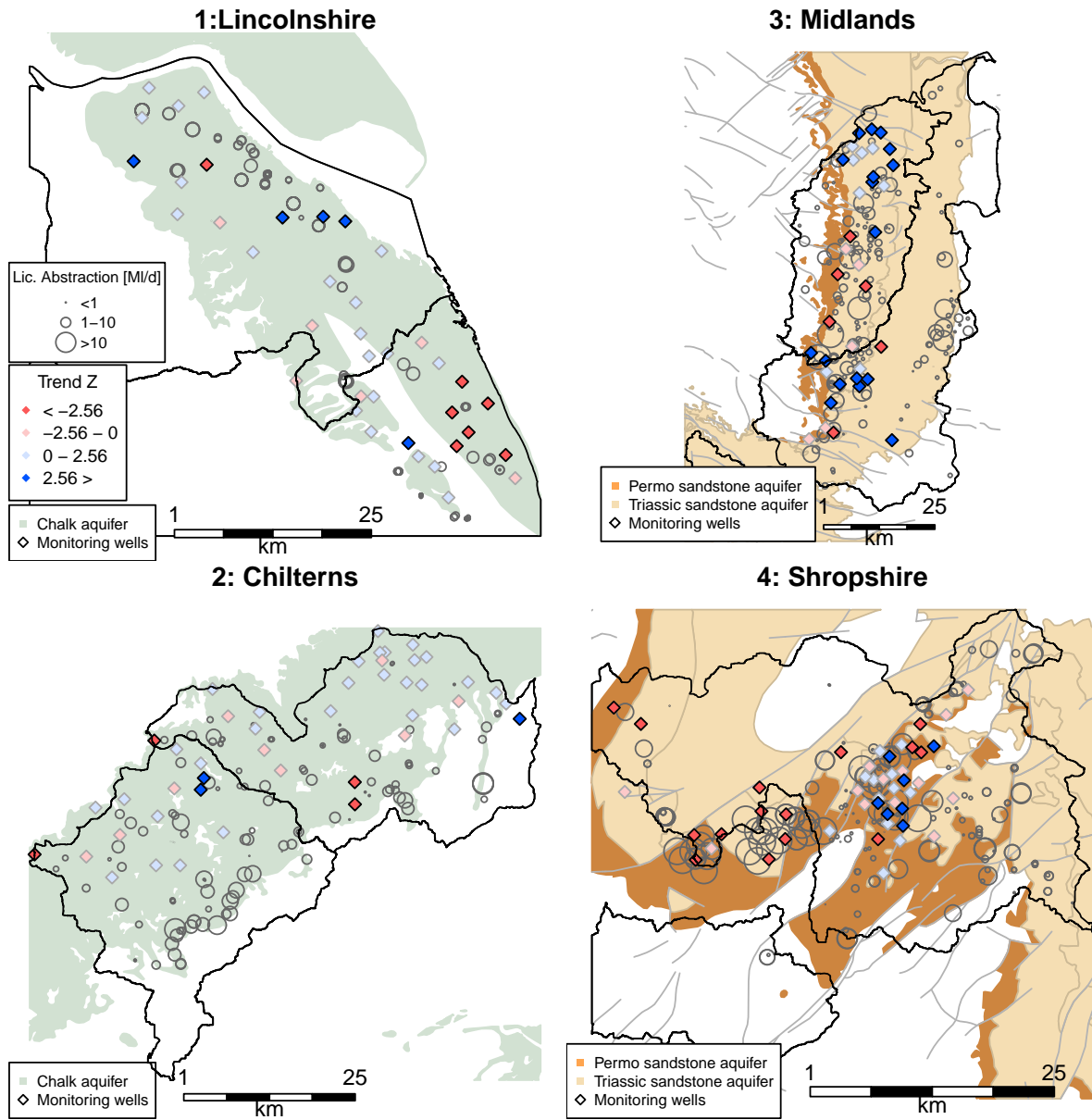
Figure 3. Trend values for monitoring wells in the four water management units (1: Lincolnshire, 2: Chilterns, 3: Midlands, 4: Shropshire). The red and blue diamonds indicate the positive or negative Z values for the Modified Mann-Kendall trend test for each monitoring well. Z values over |2.56| indicate a significant trend in the 30-year (1984-2014) groundwater time series.

relation between accumulation period and groundwater drought duration, as observed in the reference clusters, corresponds to the relation between groundwater memory and drought duration for near-natural observations, as found by Bloomfield and Marchant (2013).

Impact of groundwater use on groundwater droughts is detected in a subset of monitoring sites in all four water management units. This subset often represents a minority of monitoring sites. Two patterns are found that illustrate an asymmetric impact of water use on groundwater droughts. The first pattern (found in three water management units) is that of more, but shorter and less intense droughts that are primarily observed in the, on average, influenced sites compared to uninfluenced sites. The second pattern (found in one water management unit) shows the opposite impact with less, but longer groundwater droughts in, on average, influenced compared to uninfluenced sites. Both patterns are inferred as a direct consequence of groundwater use in the water management units.

The first pattern, apparent in Lincolnshire, Chilterns, and Shropshire, shows an increase in short drought events in influenced sites that sometimes occur before a major drought event or during unusual dry period that results in a rapid increase in both surface water and groundwater use (Walker and Smithers, 1998; Marsh et al., 2013; Durant, 2015) and/or complementary groundwater use due to surface water use restrictions (Rey et al., 2017; Rio et al., 2018). We see the effect of this local increase in water use in our data in the temporarily lowered groundwater levels resulting in additional drought events. The majority of these events occur in influenced sites, but some of the (on average) uninfluenced sites also show minor droughts. Given the high correlation in these uninfluenced sites, the minor droughts seem to not disturb the long-term average correlation. The short duration and low intensity of these additional droughts suggests that local groundwater levels recover quickly. Whether groundwater was removed from groundwater storage or capture (impacting environmental flows) remains unknown (Konikow and Leake, 2014), although the short duration and rapid recovery suggest that an equilibrium was established soon after the abstractions. Regional groundwater model studies in these three water management units show that the annual average *actual* abstractions are smaller than modelled recharge for Lincolnshire, Chilterns, and Shropshire. The ratio abstraction to recharge is 0.67 (Hutchinson et al., 2012), 0.5 (Environment Agency, 2010), 0.5 (Shepley and Streetly, 2007) for the three water management units respectively. Even though these ratios are calculated using data from different regional groundwater models, the results show that the long-term balance between groundwater use and recharge is positive, which might be related to the overall reduced drought intensity and duration for influenced sites.

The second pattern, apparent in the Midlands, shows intensified groundwater droughts that occur less often. Most of the intensified drought events are observed prior to 2001 with lengthened droughts in 1984-1986, 1990-95, 1997-2001. Lengthening of droughts is a common phenomenon in overused groundwater systems (Custodio, 2002). In the Midlands, prior to 2000, groundwater abstraction exceeded modelled recharge by 25% (Shepley et al., 2008). The overabstraction resulted in lower streamflow in the area (Shepley et al., 2008) suggesting that the balance between water removed from capture and storage was disrupted (Konikow and Leake, 2014). Reforms of water allocations in 2000 have reduced groundwater abstractions to meet the long-term water balance. These long-term changes in groundwater abstractions match with the majority of significant positive groundwater trends in the Midlands.

Long-term influence of groundwater use was inferred from identified trends in the groundwater level time series. Large spatial differences are found in the direction of groundwater trends in both aquifers, while trends in precipitation and potential evapotranspiration are negligible. Positive groundwater trends dominate in the water management units, which may be a result of the reduction of groundwater use since 1984 (start of the investigation period of this study). A gradual or immediate reduction of water use can restore the balance between groundwater use and recharge (Gleeson et al., 2010; Konikow, 2011), although it can take decades before an equilibrium is reached (Gleeson et al., 2012). This slow rise or recovery to pre-development groundwater levels is not specifically included in the classification of influenced and uninfluenced monitoring sites, as a (slow) rise in groundwater level might not disturb the propagation of precipitation anomalies. SGI and SPI anomalies could in this case synchronise well resulting in a high linear correlation, while a long-term positive trend is observed as groundwater levels slowly recover. Over longer time periods, these rising groundwater levels could also buffer precipitation anomalies. In our results, groundwater droughts show an overall reduction in magnitude and duration from 1984 to 2014. Most intense droughts are found during in the first two decades (1984-2004) of the time period. Even though this coincides with a reduction of groundwater use, more research is required to distinguish climate-driven droughts from human-modified droughts.

A conceptual typology is presented in Figure 4 summarising near-natural drought, two types of human-modified droughts as found in the water management units, and an extreme condition of human-modified drought. Under near-natural conditions, groundwater droughts occur given the climate forcing and hydrogeological setting (upper panel in Figure 4). In human-modified environments, the impact of groundwater use on groundwater droughts is asymmetric. In regions where the annual average groundwater use is smaller than the annual average recharge, the frequency of groundwater droughts increases resulting in shorter events of a lower magnitude (second panel in Figure 4). This corresponds to the 'dynamic sustainable range' as presented in the conceptual model of Gleeson et al. (2020). In regions where the annual average groundwater use approaches annual average recharge, the opposite is found with less, but prolonged droughts of higher magnitude and duration (third panel in Figure 4) corresponding to strategic aquifer depletion, when meeting the dynamic sustainable range over a long time scale (Gleeson et al., 2020). The last panel shows extreme conditions of groundwater depletion, in which groundwater droughts are not recovering by the average annual recharge and groundwater levels tend to fall consistently. These extremes conditions are not identified in the UK, but heavily intensified and lengthened droughts are found in California (He et al., 2017), Australia (Leblanc et al., 2009), Spain (Van Loon and Van Lanen, 2013), Bangladesh (Mustafa et al., 2017) and India (Asoka et al., 2017).

Further research is required to analyse the modifying effects on droughts of a change in water use over time. In this study, we have investigated the overall long-term impact of groundwater use using monotonic trends in groundwater. However, a different methodology is required to evaluate the impact of new water regulations on groundwater droughts (Bhanja et al., 2017). For example, an observation-modelling or conceptual modelling approach can be used to differentiate pre- and post-regulation groundwater droughts (Van Loon et al., 2016b; Kakaei et al., 2019; Liu et al., 2016). This future modelling work could also provide long-term context for water management effects, natural variability, non-stationary effects of anthropogenic climate change (specifically warming) on changes in groundwater drought characteristics (Bloomfield et al., 2019).
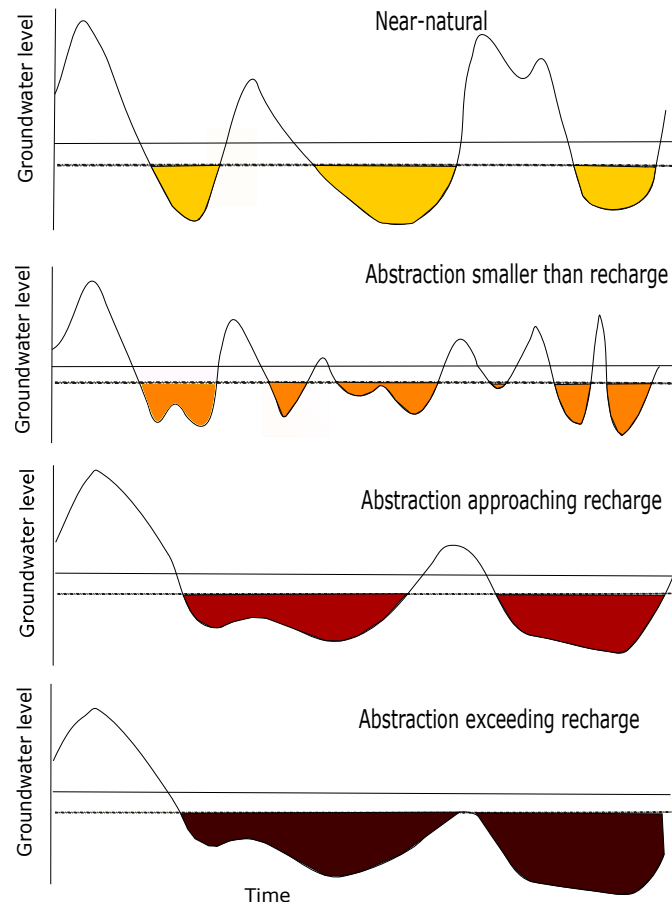
Figure 4. Conceptual figure summarising near-natural groundwater droughts (top) and three human-modified groundwater droughts with increasing intensity of impact of groundwater use. The top panel shows an example of near-natural groundwater droughts, followed by human modified droughts when annual average abstractions are smaller than the annual average groundwater recharge (second panel; identified in the three water management units in the UK). The third panel illustrates modified groundwater droughts when annual average abstractions approaches recharge (identified in one water management unit in the UK), and the last panel shows extreme groundwater drought conditions when average annual abstractions exceed recharge.

Further applications of this study could be beneficial for water regulators and scientists alike, as the presented conceptual typology can be used to investigate the impact of groundwater use without having to obtain time series of actual groundwater abstractions. The developed methodology shows how qualitative information on groundwater use and annual long-term averages aid to get a better understanding of asymmetric impact of groundwater use on groundwater droughts. Considering the large-scale modification of the hydrological cycle and the consequences for droughts (Van Loon et al., 2016a), it is important to further this approach and investigate the sustainable use of groundwater resources (Gleeson et al., 2020).

6 Conclusions

The impact of groundwater use on groundwater droughts is investigated based on a comparison of potentially influenced groundwater monitoring sites and near-natural reference sites in the UK. Results show that long-term groundwater use has an asymmetric impact on groundwater droughts for a subset of influenced groundwater monitoring sites in water management units in the UK. A conceptual typology summarises these different patterns in groundwater drought occurrence, duration, and magnitude. The first type (identified in three water management units) shows an increase in groundwater droughts with a low magnitude, of which the timing sometimes coincides with periods of a high water demand. This is found in three water management units where the long-term water balance is positive and annual average groundwater abstractions are less than groundwater recharge. The second type is marked by lengthened, more intense groundwater droughts. This is found in one water management unit where annual average groundwater abstractions temporarily exceeded recharge. The balance between long-term groundwater use and recharge seems to explain the asymmetric impact of groundwater use on groundwater droughts. However, more research is required to investigate the impact of changes in water use. During the period of investigation, regulated groundwater abstractions have reduced and our results show a majority of rising groundwater trends based on 30 years of data. Further research could potentially indicate how droughts are affected by these changes in water use.

In conclusion, this study presents a conceptual typology to analyse groundwater droughts under human-modified conditions. We found that human-modified droughts differ in frequency, magnitude, and duration dependent on the long-term proportional groundwater use compared to recharge. This highlights the relation between long-term and short-term groundwater sustainability.

Code availability. The code is available upon request.

Data availability. The raw groundwater time series and abstraction locations can be obtained via the Environment Agency. Standardised groundwater level time series is available upon request.

Author contributions. DW, AVL, BP, DH conceived and designed the study. DW performed the analysis and wrote the paper, supervised by
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Competing interests. The authors declare no conflict of interest.

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