

1 From meteorological to hydrological drought using 2 standardised indicators

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9 **Abstract**

10 Drought monitoring and early warning (M&EW) systems are a crucial component of drought
11 preparedness. M&EW systems typically make use of drought indicators such as the
12 Standardised Precipitation Index (SPI), but such indicators are not widely used in the UK. More
13 generally, such tools have not been well developed for hydrological (i.e. streamflow) drought.
14 To fill these research gaps, this paper characterises meteorological and hydrological droughts,
15 and the propagation from one to the other using the SPI and the related Standardised Streamflow
16 Index (SSI), with the objective of improving understanding of the drought hazard in the UK.
17 SPI and SSI time series were calculated for 121 near-natural catchments in the UK for
18 accumulation periods of 1-24 months. From these time series, drought events were identified
19 and for each event, the duration and severity was calculated. The relationship between
20 meteorological and hydrological drought was examined by cross-correlating the one month SSI
21 with various SPI accumulation periods. Finally, the influence of climate and catchment
22 properties on the hydrological drought characteristics and propagation were investigated.
23 Results showed that at short accumulation periods meteorological drought characteristics
24 showed little spatial variability, whilst hydrological drought characteristics showed fewer but
25 longer and more severe droughts in the south and east than in the north and west of the UK.
26 Propagation characteristics showed a similar spatial pattern with catchments underlain by
27 productive aquifers, mostly in the south and east, having longer SPI accumulation periods
28 strongly correlated with the one month SSI. For catchments in the north and west of the UK,
29 which typically have little catchment storage, standard-period average annual rainfall was
30 strongly correlated to hydrological drought and propagation characteristics. However, in the

1 south and east, catchment properties describing storage, such as base flow index, percentage of
2 highly productive fractured rock and typical soil wetness, were more influential on hydrological
3 drought characteristics. This knowledge forms a basis for more informed application of
4 standardised indicators in the UK in the future, which could aid in the development of improved
5 M&EW systems. Given the lack of studies applying standardised indicators to hydrological
6 droughts, and the diversity of catchment types encompassed here, the findings could prove
7 valuable for enhancing the hydrological aspects of drought M&EW systems in both the UK and
8 elsewhere in the world.

9 **1 Introduction**

10 Drought is widely recognised as a complex, multifaceted phenomenon (e.g. Van Loon, 2015).
11 Unlike many other natural hazards, drought develops slowly making it difficult to pinpoint the
12 onset and termination of an event. Fundamentally, a drought is a deficit in the expected
13 available water in a given hydrological system (Sheffield and Wood, 2011). Since Wilhite and
14 Glantz (1985), drought has popularly been classified into various types (e.g. meteorological,
15 hydrological, agricultural, environmental and socio-economic). The drought type generally
16 reflects the compartment of the hydrological cycle or sector of human activity that is affected;
17 deficits typically propagate through the hydrological cycle impacting different ecosystems and
18 human activities accordingly.

19 The desire to quantitatively identify and analyse drought duration, severity, onset and
20 termination has led to the development of drought indicators. Lloyd-Hughes (2014) counted
21 over 100 drought indicators in the literature, this proliferation reflecting the complexity of the
22 subject matter. It has been argued that indicators should be chosen according to the type of
23 drought in question; for example, meteorological indicators should not be used in isolation to
24 characterise hydrological drought due to the non-linear responses of terrestrial processes to
25 climate inputs (Van Loon and Van Lanen 2012; Van Lanen et al., 2013).

26 One of the primary uses of drought indicators is in monitoring and early warning (M&EW), a
27 crucial part of drought preparedness (Bachmair et al, 2015b). Little can be done to prevent a
28 meteorological drought from occurring, but actions can be taken to prevent or mitigate the
29 impact of a hydrological drought. An effective drought M&EW system is the foundation of a
30 proactive management strategy, triggering planned actions and responses (Wilhite et al., 2000).
31 There are numerous examples of drought M&EW systems globally, for example, the US
32 Drought Monitor (<http://droughtmonitor.unl.edu/Home.aspx>) and the European Drought

1 Observatory (<http://edo.jrc.ec.europa.eu>). However, comparatively few drought M&EW
2 systems incorporate hydrological variables such as streamflow; the US Drought Monitor is one
3 such example, while others rely on runoff outputs from large-scale hydrological models (e.g.
4 the Flood and Drought Monitors for Africa and Latin America; <http://stream.princeton.edu/>).
5 In many national/regional scale drought M&EW systems, the emphasis is typically placed on
6 the meteorological and/or agricultural drought hazard. As such, hydrological aspects are often
7 less sophisticated, as discussed in a recent study that combined a literature review with a survey
8 of 33 regional, national and global drought M&EW providers (Bachmair et al., 2015b).

9 The Standardised Precipitation Index (SPI; McKee et al., 1993) is one of the most widely used
10 drought indicators. It allows consistent comparison across both time and space as well as
11 providing the flexibility to assess precipitation deficits over user-defined accumulation periods.
12 The SPI also gives an indication of the severity and probability of the occurrence of a drought,
13 with increasingly negative values indicating a more severe, yet less likely, drought (Lloyd-
14 Hughes and Saunders, 2002). Despite the advantages and flexibilities of the SPI, there are
15 known deficiencies. The choice of an appropriate probability distribution is still under
16 investigation in the literature (e.g. Stagge et al., 2015; Svensson et al., 2015b) and the fitting of
17 a probability distribution function to data with a high proportion of zeros can be problematic
18 (Wu et al., 2007). It has also been noted that as the SPI accumulation period increases, the
19 spatial behaviour of the index becomes more fragmented making it more difficult to identify
20 regions with similar patterns of drought evolution (Vicente-Serrano, 2006). Notwithstanding
21 these deficiencies, the relative simplicity of calculation, comparability and flexibility of the SPI
22 have led to an endorsement by the World Meteorological Organization as the indicator of choice
23 for monitoring meteorological drought (Hayes et al., 2011). The use of precipitation alone does
24 not take evaporative demand into account, which may result in drought severity being
25 underestimated in regions or seasons with high levels of evapotranspiration. This led to the
26 development of the Standardised Evapotranspiration Index (SPEI; Vicente-Serrano et al.,
27 2010). A growing trend in drought M&EW research is the application of the same
28 standardisation principles to other hydrological data types (soil moisture, streamflow,
29 groundwater etc.) producing a family of standardised indices for all compartments of the
30 hydrological cycle (Bachmair et al., 2015b).

31 In the UK, there is no nationwide, drought-orientated M&EW system in place. Regular
32 hydrological reporting, published by the National Hydrological Monitoring Programme in

1 monthly Hydrological Summaries (<http://nrfa.ceh.ac.uk/nhmp>), uses simple rank-based
2 approaches to place current hydrological conditions in their historical context. Although it is a
3 valuable resource, it is not used for drought planning and does not trigger actions in drought
4 plans. Drought M&EW is carried out individually by regulators (such as the Environment
5 Agency in England, who produce monthly Water Situation Reports; Environment Agency,
6 2015) and water companies, who also typically use simple rank-based indicators to examine
7 drought status according to their own drought plans (e.g. Thames Water; Thames Water, 2013).
8 While there is already very effective consultation between different stakeholders in drought
9 planning, there are inevitably differences in interpretation and communication of droughts.
10 There is a recognised need to develop more consistent approaches to monitoring (Collins et al.,
11 2015), highlighting the potential benefit of a large-scale drought M&EW system tailored to a
12 range of end-user needs.

13 The absence of a coherent drought-focused M&EW system across the UK is, in part, due to the
14 lack of consensus on appropriate drought indicators or drought definitions for the UK. A
15 number of drought analyses have been applied using a range of non-standardised indicators
16 (e.g. Marsh et al., 2007; Rahiz and New, 2012; Watts et al., 2012) but the SPI and other
17 standardised indicators have only been used in a few research studies (e.g. Hannaford et al.,
18 2011; Lennard et al., 2015; Folland et al., 2015). Such indicators are generally not used
19 operationally; although the Scottish Environment Protection Agency use a variant of
20 standardised indicators for drought M&EW (Gosling, 2014) and Southern Water use SPI in
21 their drought plan (Southern Water, 2013).

22 Recently, there has been growing interest in applying the standardised family of indicators at
23 the national scale in the UK. A Drought Portal (<https://eip.ceh.ac.uk/droughts>) has been
24 developed to visualise past meteorological drought using gridded SPI data (Tanguy et al., in
25 preparation); and a version of the Standardised Streamflow Index (SSI), for hydrological
26 drought, has been developed (Svensson et al., 2015b). Despite these advances, a major obstacle
27 to the development of a drought-focused M&EW system is a lack of understanding of how
28 meteorological deficits propagate to hydrological drought. Folland et al. (2015) explored
29 propagation between meteorological, streamflow and groundwater drought using standardised
30 indicators. However, the study focused on regional averages for a single large region in south-
31 east England and the authors acknowledged that there is likely to be significant spatial
32 variability in propagation as a result of the diverse climate and geology across the UK. Several

1 studies have demonstrated the importance of catchment properties in modulating precipitation
2 signals in UK streamflow (Laizé and Hannah, 2010; Chiverton et al., 2015a) and this has been
3 shown specifically for drought (Fleig et al., 2011). As such, there is a need for a fuller
4 understanding of regional variability in drought characteristics, how this variability is affected
5 by the propagation from meteorological to hydrological drought, and which climatic and
6 catchment properties influence these relationships.

7 Many studies investigating hydrological drought characterisation and drought propagation have
8 done so at the national, continental or global scale using modelled data (e.g. Vidal et al., 2010;
9 Van Lanen et al., 2013), or at a smaller scale using a limited number of sites and observed data
10 (e.g. Fleig et al., 2011; López-Moreno et al., 2013; Lorenzo-Lacruz et al., 2013b; Haslinger et
11 al., 2014). Furthermore, few studies have used standardised indicators for both meteorological
12 and hydrological droughts, which enables consistent characterisation across components of the
13 hydrological cycle (and thereby potentially forming the foundation of a more integrated drought
14 M&EW system). Very few observational studies have addressed the influence of climate and
15 catchment properties on drought characteristics and propagation in a wide range of catchments
16 demonstrating climatic and geological diversity. Studies have also tended to focus on a few
17 characteristics representing geology or climate (e.g. Vidal et al., 2010; Lorenzo-Lacruz et al.,
18 2013b; Haslinger et al., 2014) rather than a wide range of physiographic and land use properties,
19 with the exception of the study by Van Loon and Laaha (2015) that used 33 catchment
20 properties.

21 This study exploits the long streamflow and precipitation records held by the National River
22 Flow Archive (NRFA) for 121 catchments. Using observed data, the utility of standardised
23 indicators, the Standardised Precipitation Index (SPI) and the Standardised Streamflow Index
24 (SSI), for characterising drought characteristics and propagation behaviour is assessed,
25 specifically addressing the following key questions:

- 26 1. How do meteorological and hydrological drought characteristics vary spatially across
27 the UK?
- 28 2. Over which time scales are meteorological and hydrological droughts related?
- 29 3. Which climatic and catchment properties influence hydrological drought characteristics
30 and the propagation from meteorological to hydrological drought?

31 Addressing these questions will supplement the existing knowledge of the baseline drought
32 hazard and propagation behaviours across the UK, in a set of catchments with diverse

1 properties, representative of hydro-climatic and landscape variations. This knowledge is an
2 important foundation for the development of improved drought M&EW systems (Folland et al.,
3 2015; Van Loon, 2015) allowing preventative measures to be implemented resulting in reduced
4 vulnerability and increased resilience to drought.

5 **2 Data**

6 The UK has one of the densest hydrometric networks in the world. Hydrometric data is archived
7 and curated by the NRFA (<http://nrfa.ceh.ac.uk>), which holds data for around 1400 gauging
8 stations (Dixon et al., 2013). The Benchmark catchments are a subset of these gauging stations
9 with good hydrometric performance and near-natural flow regimes (Bradford and Marsh,
10 2003). It was necessary to limit the study to these catchments as major artificial influences
11 could confound the identification of links between meteorological and hydrological drought;
12 regulated catchments have been shown to be distinctly different in terms of hydrological
13 drought characteristics (e.g. Lorenzo-Lacruz et al., 2013b).

14 The selected Benchmark catchments were required to have at least 30 years of daily streamflow
15 records 1961-2012 and each month was required to have at least 25 days of valid observations
16 (in order to calculate mean monthly streamflow). Two ephemeral streams were excluded from
17 the selection, as the truncation of the flows at zero would have been unhelpful when studying
18 drought propagation. The selection criteria resulted in 121 catchments, providing good spatial
19 coverage of the UK and a range of catchment types (Fig. 1). The selection of Benchmark
20 catchments used here differs slightly to other published studies (e.g. Hannaford and Marsh,
21 2006; Chiverton et al., 2015a) because of differing selection criteria and the ongoing evolution
22 of the Benchmark network. The NRFA also holds catchment average monthly precipitation data
23 for each catchment based on observed UK Met Office data (Met Office, 2001; Marsh and
24 Hannaford, 2008). At least 30 years of catchment average monthly precipitation data were
25 available for each catchment between 1961 and 2012. In some cases, the catchment average
26 monthly precipitation and mean monthly streamflow period of record differed in length, but all
27 catchments had at least 30 years of data overlapping 1961-2012. Less than 10% of catchments
28 had a difference in record length of five or more years, and less than 3% of catchments had a
29 difference in record length of 10 or more years. When data completeness was calculated from
30 the start of the catchment average monthly precipitation and mean monthly streamflow record,
31 the proportion of missing data for each catchment was, on average, less than 0.01% of months
32 for precipitation data and less than 2% of months for streamflow data.

1 Catchments were clustered using a previously developed classification system (Chiverton et al.,
2 2015a) based on the temporal dependence in daily streamflow (characterised by calculating
3 semi-variograms), enabling calculated drought characteristics to be analysed regionally. Where
4 the catchments overlapped with those used in Chiverton et al. (2015a), the same cluster
5 allocations were used. The 15 catchments that did not overlap between the two studies were
6 assigned to the cluster for which the semi-variogram was closest to the mean semi-variogram
7 of the cluster. Figure 1 shows the distribution of clusters across the UK for the 121 selected
8 catchments. Clusters one and two are predominantly located in the upland north and west of the
9 UK, have steeper slopes, less storage, are less permeable and have a higher amount of
10 precipitation than the catchments in clusters three and four which are mostly located in the south
11 and east of the UK. Predominant soil types differ between all four clusters. Clusters one and
12 two can also be differentiated by elevation while clusters three and four can be differentiated
13 by their geology (Chiverton et al., 2015a).

14 Nine catchments covering a range of catchment types and sizes, as well as each cluster, were
15 selected as case study catchments (Fig. 1) to allow more detailed, catchment-scale results to be
16 displayed in this article.

17 The catchment average SAAR (standard-period average annual rainfall) 1961-1990 was used
18 as a descriptor of the precipitation climate. The SAAR values were derived from a 1km gridded
19 map based on Met Office data (Spackman, 1993). In order to investigate the influence of the
20 physical catchment on drought propagation, catchment properties were extracted for each
21 catchment. The selected catchment properties (Table 1) have been found in previous studies to
22 be significant for modifying climate-streamflow associations and in determining the temporal
23 dependence of flows (Laizé and Hannah, 2010; Chiverton et al., 2015a). Base flow index (BFI),
24 calculated from streamflow data (Gustard et al., 1992), although not technically a catchment
25 property, has been found to reflect catchment geology, storage and release properties and so
26 was used as an indicator of catchment storage (Bloomfield et al., 2009; Hidsal et al., 2004; Van
27 Loon and Laaha, 2015). Catchment properties were derived from spatial data held by the NRFA
28 (Marsh and Hannaford, 2008), the British Geological Survey, and in some cases extracted from
29 the Flood Estimation Handbook (FEH; Bayliss, 1999).

1 **3 Methods**

2 **3.1 Drought characteristics**

3 The Standardised Precipitation Index (SPI) is calculated by first aggregating precipitation data
4 over a user-defined accumulation period (often 1, 3, 6, 12 or 24 months). A probability
5 distribution function is then fitted to the aggregated precipitation data for each calendar end-
6 month (of the accumulation period) individually. It is then transformed to the standard normal
7 distribution with a mean of zero and a standard deviation of one. This transformation makes the
8 SPI comparable over time and space. The calculated SPI value represents the number of
9 standard deviations away from the typical accumulated precipitation (McKee et al., 1993;
10 Guttman, 1999; Lloyd-Hughes and Saunders, 2002). For SPI calculation, a Gamma distribution
11 is often fitted to precipitation data. Several studies have tested the most appropriate probability
12 distribution to fit to precipitation data and in many cases found Gamma to be acceptable (e.g.
13 Guttman, 1999; Stagge et al., 2015). The Standardised Streamflow Index (SSI) uses the same
14 principle as the SPI, aggregating streamflow data over the given accumulation periods (Vicente-
15 Serrano et al., 2012b; Lorenzo-Lacruz et al., 2013a). In contrast to precipitation and SPI
16 calculation, there is no widely adopted probability distribution function fitted to streamflow
17 data for SSI calculation and previously, numerous probability distribution functions have been
18 used (e.g. Vicente-Serrano et al., 2012a). Here, we fit the Tweedie distribution, which has been
19 shown to fit the same catchments well (Svensson et al., 2015b), for both catchment average
20 monthly precipitation and mean monthly streamflow. The Tweedie distribution is a flexible
21 three-parameter distribution that has a lower bound at zero (Tweedie, 1981; Jørgensen, 1987).
22 The ‘SCI’ package for R (Gudmundsson and Stagge, 2014) was used to calculate SPI and SSI
23 for the period 1961-2012 and accumulation periods of 1-24 months. A new function enabled
24 the parameter estimation in the ‘tweedie’ package for R (Dunn, 2014) to be called within the
25 SCI package (Svensson et al., 2015b). Accumulation periods are denoted as follows: SPI-x and
26 SSI-x, for example, SPI-6 and SSI-3 correspond to a six month precipitation accumulation
27 period and a three month streamflow accumulation period, respectively.

28 Drought events were defined as periods where indicator values were continuously negative with
29 at least one month in the negative series reaching a given threshold (McKee et al., 1993; Vidal
30 et al., 2010). Thresholds of -1 (moderate drought), -1.5 (severe drought) and -2 (extreme
31 drought; Lloyd-Hughes and Saunders, 2002) were used to identify drought events. The total
32 number of events was calculated for each catchment, accumulation period and threshold in

1 addition to the mean, median and maximum event duration and severity. The duration of each
2 individual event was calculated for the given catchment at a monthly resolution. The severity
3 was calculated by summing the SPI/SSI values across all constituent months of each identified
4 event in each catchment (Vidal et al., 2010) and as such has no units.

5 Missing catchment average monthly precipitation/mean monthly streamflow data would mean
6 that no SPI or SSI value was calculated, potentially affecting duration/severity characteristics
7 for some events. However, visual inspection of the data confirmed that for major UK drought
8 events (Marsh et al., 2007), the impact of missing data was minimal and isolated to only a few
9 catchments for streamflow data, and, there was no missing precipitation data for major events.
10 This and the low proportion of missing data in the datasets as a whole (Sect. 2) suggest the
11 incidental months of missing data are localised and unlikely to have had a significant impact
12 on the extracted drought characteristics.

13 **3.2 Drought propagation**

14 Streamflow, and so the SSI, integrates catchment scale hydrogeological processes. As such, a
15 comparison with the SPI provides an indication of the time taken for precipitation deficits to
16 propagate through the hydrological cycle to streamflow deficits. SPI accumulation periods of
17 1-24 months and SSI-1 time series were cross-correlated using the Pearson correlation
18 coefficient to analyse the most appropriate accumulation period of SPI to characterise to SSI-
19 1. The one month SSI also provides a good description of low flows, similar to the 30-day mean
20 flow, which is often used in studies of annual minimum flows (e.g. Gustard et al., 1992). The
21 SPI accumulation period with the strongest correlation with SSI-1 was denoted SPI-n and was
22 used as an indicator for drought propagation. Where SSI-1 was most strongly correlated to short
23 SPI accumulation periods, the propagation time is also short, and vice versa. To determine
24 whether there is a lag between the SPI (accumulation periods of 1-24 months) and SSI-1, cross-
25 correlations were calculated for SSI-1 series which were lagged by zero to six months after the
26 SPI series. In this case, the duration of the SPI accumulation period with the strongest
27 correlation with SSI-1 was denoted as the lagged SPI-n.

28 Independence of data is a requirement for many statistical analyses. However, because of
29 temporal dependence, or autocorrelation, in the SSI-1 and in all the series of SPI accumulation
30 periods exceeding one month, data are not independent. Correlations between two
31 autocorrelated time series have fewer effective degrees of freedom than is assumed in a standard

1 significance test. As such, using a standard significance test can result in an increased chance
2 of concluding correlations are statistically significant (i.e. increased rate of Type 1 error; Pyper
3 and Peterman, 1998). In order to address and control Type 1 error rates, the ‘modified Chelton’
4 method outlined in Pyper and Peterman (1998) was adapted to account for missing data, and
5 used for calculating the effective degrees of freedom for a given data series. Details of the
6 ‘modified Chelton’ method are provided in the supplementary material (S1).

7 **3.3 Links with climate and catchment properties**

8 Hydrological drought characteristics were plotted against SAAR (standard-period average
9 annual rainfall) and the corresponding correlation coefficients calculated. Spearman’s
10 correlation was used because of the non-linear relationships between the hydrological drought
11 characteristics and SAAR. Clusters one and two were grouped together because of their location
12 in the windward mountainous north and west of the country and clusters three and four were
13 grouped together because of their location in the sheltered lowland south-east. Spearman’s
14 correlations were also used to quantify the relationship between the hydrological drought
15 characteristics and catchment properties described in Table 1.

16 **4 Results**

17 **4.1 Drought characteristics**

18 For each accumulation period and catchment, drought events were identified using thresholds
19 of -1, -1.5 and -2 (moderate, severe and extreme drought, respectively). For both SPI and SSI,
20 unsurprisingly, more drought events were identified at shorter accumulation periods and
21 thresholds closest to zero. As the accumulation period lengthens and the threshold moves away
22 from zero, the number of events decreases, duration lengthens and severity worsens (Table 2).
23 Spatial patterns for the SPI and SSI maximum duration and severity characteristics were similar
24 for all three thresholds, and as such, only results for the -2 threshold (extreme drought) are
25 shown. Results for the -1 and -1.5 thresholds can be found in the supplementary material (S2;
26 Fig. S1, Fig. S2, Fig. S3 and Fig. S4).

27 For SPI-1, SPI-6 and SPI-18, there is little variation between the four clusters of catchments for
28 the number of events and the median drought duration/severity characteristics (Fig. 2). This
29 indicates that meteorological drought characteristics vary only modestly across the country over
30 shorter accumulation periods once the precipitation has been standardised. The maximum

1 duration/severity characteristics showed more differences between clusters, often showing a
2 gradual change from cluster one to four. For SPI-1 the maximum duration of droughts in cluster
3 one were generally short (between four and nine months) whilst those in cluster four were
4 longer (between 4 and 11 months). Similarly, for SPI-1 maximum severity, droughts in cluster
5 one were less severe than those in cluster four. In contrast, the maximum duration and severity
6 for SPI-6 was similar across all clusters whilst for SPI-18 the median of the maximum duration
7 decreases when moving from clusters one to three; the median of cluster four is higher than that
8 of cluster two. The median maximum severity shows a different pattern for SPI-18 than for the
9 shorter accumulation periods – median severity increases (becomes less severe) moving from
10 cluster one to three; cluster four has a lower (more severe) median severity than cluster three.
11 Over these longer accumulation periods, inter-annual variability starts to become more
12 influential; however, as will be discussed below (Sect. 5.1), the findings are somewhat
13 surprising given that cluster one (mostly north-west Britain, the wettest and most upland part
14 of the country) displays the longest drought durations and most severe events.

15 Maps of meteorological drought characteristics based on SPI-1 and SPI-6 (Fig. 3) again show
16 little spatial variability in either the number of events or event duration and severity. The
17 number of events at the 18-month accumulation period also shows little spatial variability;
18 however, the duration and severity maps show longer, more severe meteorological drought
19 events occurring in northern England and Scotland.

20 For SSI (Fig. 4), there is a larger difference between the clusters for SSI-1 and SSI-6 than is
21 seen in SPI for the same accumulation periods (Fig. 2). As was the situation for SPI-1, the
22 differences between clusters occurs gradually from cluster one to four. For SSI-1 fewer, but
23 longer and more severe, events are identified in cluster four than cluster one. As the SSI
24 accumulation period increases to 18 months, there is less difference between the clusters (Fig.
25 4); much like the spatial trends seen for SPI-18 (Fig. 2), whereby cluster one has a much greater
26 range in maximum duration and severity than the other three clusters.

27 Maps of hydrological drought characteristics based on SSI show more spatial variability (Fig.
28 5) than the meteorological drought characteristics (Fig. 3). For SSI-1 and SSI-6, fewer, longer,
29 more severe events occur in the south and east. As the accumulation period lengthens to 18
30 months, longer, more severe events occur in Scotland and the north of England. Despite this,
31 the number of events remains fewer than 10 throughout the UK with the most events occurring
32 in the south-east of England.

1 Time series plots of SPI for selected accumulation periods in Fig. 6 and SSI in Fig. 7 show the
2 highly variable time series for the one month accumulation period. As the accumulation period
3 increases to six and 18 months, the time series become smoothed with both wet and dry periods
4 becoming more prolonged. Figure 6 also shows that at the longer accumulation period (SPI-18)
5 for the two Scottish case study sites (River Dee and River Cree), the early time series is
6 dominated by dry events, while the later time series is dominated by wet events. This is in
7 contrast to the remaining case study sites in England and Wales, which show more regular
8 fluctuations between wet and dry events throughout the SPI time series. Similar long-term
9 trends can be seen in the SSI time series for the case study catchments in Fig. 7. The
10 implications of these patterns for application of the SPI and SSI will be returned to in the
11 discussion (Sect. 5.1).

12 **4.2 Drought propagation**

13 Pearson correlations between SSI-1 and different accumulation periods of SPI (1-24 months)
14 showed that for the majority of catchments, the SPI-n (i.e. the SPI accumulation period with
15 the strongest correlation with SSI-1) duration was one, two and three months (50, 38 and 10
16 catchments respectively, Fig. 8). The longest SPI-n duration was 19 months (r value associated
17 with SPI-n=0.85) followed by 16 months (r value associated with SPI-n=0.83), both located in
18 south-east England.

19 Figure 8 shows that for catchments in the north and west of the UK SPI-n durations were
20 between one to four months, whilst longer SPI-n durations were found in the south and east.
21 The most northerly catchment where the SPI-n duration is longer than four months was on the
22 east coast where SSI-1 was most strongly correlated with SPI-12 ($r=0.80$). The location of
23 catchments with longer SPI-n durations in the south and east mostly coincide with the location
24 of major UK aquifers (Fig. 8); the relationship between this indicator of drought propagation
25 and physical catchment properties will be explored further in Sect. 4.3.

26 Figure 9 shows the correlations between all SPI accumulation periods (1-24 months) and SSI-
27 1. The strength of the correlations reflects the spatial variability seen in SPI-n (Fig. 8).
28 Catchments in the north and west show the strongest correlations at accumulation periods of 6
29 months or less, a majority of which (particularly in western Britain) show the maximum
30 correlation at SPI-1, compared with those in the south and east where strong correlations are
31 found at the full range of SPI accumulation periods (1-24 months). Some catchments do not fit

1 this geographical generalisation. For example, some catchments in Scotland and Wales show
2 strong correlations between SPI and SSI-1 across a range of SPI accumulation periods, whilst
3 several catchments in south-east England show the strongest correlation at short SPI
4 accumulation periods and weaker correlations at longer SPI accumulation periods.

5 When SPI values (for accumulation periods of 1-24 months) were correlated with lagged SSI-
6 1, the strongest correlation was found at a lag of zero months (i.e. no lag) for all catchments.
7 One would expect the duration of the SPI accumulation period most strongly correlated with
8 lagged SSI-1 (lagged SPI-n) to be a function of the autocorrelation in the SSI-1 time series. To
9 examine this, the longest n-month period for which there is significant autocorrelation in SSI-
10 1 ($\alpha=0.05$; autocorrelation max) is also shown in Fig. 10 on the y-axis for the SSI-1 with zero
11 lag. For the nine case study catchments, the autocorrelation max is very close to (in all cases
12 within 4 months) the lagged SPI-n duration. The autocorrelation max for the Cree occurs at
13 zero months (and so is not shown in Fig. 10) showing there is no month-to-month
14 autocorrelation in the flows. When looking at all catchments (as in Fig. 9), the lagged SPI-n
15 duration and the autocorrelation max was the same or one month different for over 80% of
16 catchments.

17 Case study catchments in the south and east (Harpers Brook, Thet, Lambourn and Great Stour)
18 show stronger and significant ($\alpha=0.05$) correlations across a range of both SPI accumulation
19 periods and lags than those in the north and east (Dee, Cree, South Tyne, Teifi and Torridge;
20 Fig. 10). These northern and western catchments show strong, significant correlations at shorter
21 SPI accumulation periods and lags and as lag increases the strength and significance of
22 correlations decreases. Case study catchments in the north and west (south and east) can be
23 characterised by generally low (high) BFI values. For all catchments, there was a strong
24 correlation between the lagged SPI-n duration and BFI ($r=0.79$, $\alpha=0.001$). Although BFI
25 showed a strong correlation with the lagged SPI-n duration, because of the climatic, geological
26 and land-surface heterogeneity in the UK, other climate and catchment properties are also likely
27 to be influential; these are discussed in the following section (Sect. 4.3).

1 **4.3 Links with climate and catchment properties**

2 **4.3.1 Relative importance of rainfall and catchment storage on hydrological** 3 **droughts across clusters**

4 Table 3 shows the Spearman correlations between hydrological drought characteristics (based
5 on SSI and include a propagation indicator, SPI-n duration) and SAAR for clusters one and
6 two, clusters three and four and all catchments grouped together. The Spearman correlations
7 for all catchments showed stronger, highly significant correlations ($\alpha=0.001$) between SAAR
8 and the hydrological drought characteristics. Correlations for clusters one and two are stronger,
9 and significant ($\alpha=0.01$), than those for clusters three and four which were weak and non-
10 significant. This suggests that the general precipitation climate is more influential in
11 determining hydrological drought characteristics and propagation in clusters one and two than
12 it is in clusters three and four, where the within-cluster precipitation climate is uniform and the
13 geology is more heterogeneous. However, the significance of these correlations is likely to be
14 a result of a) the strong precipitation gradient between the north-west and the south-east of the
15 UK; and b) the unequal number of catchments in each group – there are 71 catchments in
16 clusters one and two and 50 catchments in clusters three and four.

17 Figure 11 shows the relationship between SAAR and hydrological drought characteristics for
18 all catchments, with points coloured by BFI to give an indication of the relationship between
19 the hydrological drought characteristics and catchment storage. The plots show BFI decreasing
20 as SAAR increases, a reflection of the fact that most high BFI, i.e. high storage, catchments are
21 located in lowland south-east England that receives less precipitation. Figure 11 shows positive
22 relationships between SAAR and median/maximum severity but as SAAR reaches ~1000mm,
23 there is little change in the hydrological drought and propagation characteristics for further
24 increases in SAAR. There was a negative correlation between SAAR and median/maximum
25 duration and SPI-n duration but again, there was little change in the hydrological drought and
26 propagation characteristics for SAAR values over 1000mm. The strong, significant ($\alpha=0.001$)
27 relationships for all catchments between SAAR and the hydrological drought characteristics are
28 shown in Table 3.

29 Figure 12 shows the relationship between SAAR, hydrological drought characteristics and
30 propagation but for catchments in clusters three and four only (the results for clusters one and
31 two are not shown as they are broadly similar to the results for the full dataset). The relationship

1 with SAAR for these clusters, as shown in Table 3, is weaker than those for all catchments
2 (Table 3, Fig. 11). Instead, it is clear that catchments from clusters three and four can be split
3 into two groups, those with higher BFI values and those with lower BFI values (Fig. 12);
4 catchments were split based on the median BFI for clusters three and four. Each group
5 separately follows the same relationship with SAAR, as described for the full data set in Table
6 3 and Fig. 11. This is with the exception of the r value associated with SPI-n and SAAR, which
7 shows opposite relationships – positive (negative) for low (high) BFI catchments. These results
8 show that SAAR is strongly correlated to hydrological drought and propagation characteristics
9 for catchments in clusters one and two. For catchments in clusters three and four, catchment
10 storage, as indexed by BFI, is more influential in determining hydrological drought
11 characteristics and propagation than precipitation. The following section considers whether
12 catchment properties, including those that describe and influence storage, can explain
13 hydrological drought and propagation characteristics.

14 4.3.2 Influence of catchment properties on hydrological droughts

15 Hydrological drought characteristics for clusters one and two showed strong correlations with
16 elevation properties. This, in conjunction with the strong correlations between the hydrological
17 drought characteristics and SAAR (Table 3) indicate that the climatological control is the
18 dominant factor influencing hydrological drought characteristics in the typically wet, upland
19 catchments of clusters one and two mainly located in the north and west of the UK. The
20 variation in precipitation across the lowland south and east is relatively minor in comparison to
21 the north and west of the UK, but exhibits heterogeneity in geology and land cover, allowing
22 catchment properties to exert a greater control on the hydrological drought characteristics in
23 clusters three and four. As such, in the following sections, only results for clusters three and
24 four are presented and discussed. The correlations between hydrological drought characteristics
25 and catchment properties for clusters one and two can be found in the supplementary material
26 (S3; Fig. S5).

27 Figure 13 shows that when clusters three and four are grouped together, both the median and
28 maximum hydrological drought duration have a strong positive correlation with catchment
29 properties related to storage, such as the percentage of highly productive fractured rock ($r=0.78$
30 and 0.59 , respectively) and BFI ($r=0.73$ and 0.56 , respectively). Correlations of catchment
31 properties with severity characteristics were generally of a similar strength, but where duration
32 characteristics showed positive correlations, severity characteristics showed negative

1 correlations (and vice versa). The number of events was most strongly correlated to the
2 percentage of highly productive fractured rock ($r=-0.70$) and BFI ($r=-0.68$), both of which were
3 significant ($\alpha=0.001$). These two catchment properties were also most strongly correlated to the
4 SPI-n duration ($r=0.81$ and 0.83 , respectively). The percentage of highly productive
5 intergranular rocks showed significant relationships with all hydrological drought
6 characteristics ($\alpha=0.001$), whilst the percentage of moderately productive intergranular rocks
7 showed weaker and less significant relationships ($\alpha=0.1$, 0.01 or 0.001). The percentage of low
8 productivity intergranular rocks on the other hand, showed negative correlations where the
9 percentage of highly and moderately productive intergranular rocks showed positive
10 correlations, and both duration characteristics and SPI-n duration correlations were significant
11 ($\alpha=0.1$).

12 PROPWET has significant correlations with all the hydrological drought characteristics (except
13 the r value associated with SPI-n). Positive relationships were found between PROPWET and
14 the number of events, severity characteristics and the r value associated with SPI-n. The
15 remaining hydrological drought characteristics had negative correlations with PROPWET. The
16 percentage of shallow gleyed soils were third most strongly correlated with the number of
17 events, median duration and median severity. It showed similar correlations to those of
18 PROPWET, but correlations were generally stronger and more significant. The percentage of
19 peat soils showed similar, if weaker and less significant, correlations to the percentage of
20 shallow gleyed soils and PROPWET. The percentage of no gleyed soil showed correlations of
21 a similar strength and significance to the percentage of shallow gleyed soils but of the opposite
22 sign (i.e. where the percentage of shallow gleyed soils correlations were positive, the percentage
23 of no gleyed soils were negative, and vice versa). In contrast the percentage of deep gleyed soils
24 showed very weak or no correlation with the hydrological drought characteristics.

25 The percentage of arable land and grassland were significantly correlated for all hydrological
26 drought characteristics ($\alpha=0.1$, 0.01 or 0.001), with the exception of the r value associated with
27 SPI-n. The percentage of grassland showed correlations of the opposite sign, where the
28 percentage of arable land had a positive correlation with hydrological drought characteristics
29 the percentage of grassland had a negative correlation. The percentage of woodland showed
30 significant correlations, of the same sign as the percentage of grassland, between the number of
31 events, median duration, median severity, maximum severity ($\alpha=0.1$) and SPI-n duration
32 ($\alpha=0.01$).

1 All hydrological drought and propagation characteristics were weakly correlated to catchment
2 properties such as area, slope, the percentage of mountain, heathland and bog and elevation
3 properties (generally non-significant). The use of ‘near natural’ Benchmark catchments meant
4 that they are little influenced by urban areas or regulation, as such the catchment properties
5 urban extent and FARL were excluded from the analysis.

6 **5 Discussion**

7 **5.1 Drought characteristics**

8 Drought characteristics were extracted from SPI and SSI time series from a wide and
9 representative sample of UK catchments. This provides a comprehensive view of
10 meteorological and hydrological droughts at the national scale, assessed using the standardised
11 indicators that have been relatively under-used in the UK. Overall, the results show that, for
12 shorter accumulation periods, there is comparatively little difference between catchment types
13 (as shown by the clusters, Fig. 2) or around the country in meteorological drought
14 characteristics extracted from SPI time series (Fig. 3). Although the UK has an order of
15 magnitude precipitation gradient across the country, there is little difference in the median of
16 the meteorological drought characteristics. Similarly, Van Loon and Laaha (2015) found little
17 spatial variation in the number and average duration of meteorological events between clusters
18 of Austrian catchments. However, this study shows that there are pronounced regional
19 differences in the maximum drought duration and severity, which is supported by Folland et al.
20 (2015) who note that the north-west has a more variable climate and the south-east is subject to
21 longer dry spells, and that in practice the two regions experience droughts in opposition.
22 Regional differences in meteorological drought duration and severity have also been found
23 elsewhere, e.g. in Valencia where spatial variation was found to be the result of both catchment
24 relief and climatic variability across the region (Vicente-Serrano et al., 2004).

25 In contrast, hydrological drought characteristics extracted from SSI time series show distinct
26 regional variations and differences between catchment types. SSI-1 and SSI-6 results show
27 fewer, longer, more severe droughts occurring in southern and eastern regions of England,
28 which are dominated by groundwater-fed rivers on permeable aquifer outcrops (Fig. 4 and Fig.
29 5). These results parallel those seen in Vidal et al. (2010), who found fewer, but longer, more
30 severe events in gridded, modelled streamflow data in northern France, which is dominated by
31 groundwater-fed rivers and large aquifer systems, than in southern France. These results show

1 that although standardisation is carried out for each month, the month-to-month autocorrelation
2 in streamflow means that droughts defined using a given SSI threshold can take on very
3 different characteristics around the country, according to hydrological memory.

4 Given the climatological gradient in the UK, the long, severe droughts identified using SPI-18
5 and SSI-18 in Scotland were unexpected (Fig. 3 and Fig. 5). Previous studies characterise
6 droughts in Scotland as being shorter and less severe than those in the south and east of England
7 (Jones and Lister, 1998; Marsh et al., 2007). These apparent long droughts are a result of strong
8 long-term increasing temporal trends in run-off, primarily driven by the inter-decadal
9 variability in the North Atlantic Oscillation, as have been widely reported (e.g. Hannaford,
10 2015). As there is a strong trend, the standardised approach makes it appear that there is one
11 long drought in the early record, and pronounced wetness at the end (Fig. 6 and Fig. 7). In one
12 sense, this is a perfectly valid finding, the dryness of the early period is important in if
13 examining long meteorological droughts. However, in another sense, it is misleading, as
14 ‘droughts’ (in terms of triggering a particular impact) of 18 months duration are less influential
15 on reservoir levels and water resources planning in the north and west of the UK. This is, in
16 part, due to the lack of sub-surface storage in these responsive catchments. A short and
17 intermittent wet spell can return the catchment to normal conditions as there is limited storage
18 in which to build up deficits. The dangers of using standardised indicators in the presence of
19 non-stationarity and multi-decadal variability in atmosphere/ocean drivers have been
20 highlighted elsewhere (e.g. McCabe et al. 2004; Núñez et al. 2014)

21 **5.2 Drought propagation**

22 SSI-1 was cross-correlated with SPI accumulation periods of 1-24 months to identify the time
23 scale over which precipitation deficits propagate through the hydrological cycle to produce
24 streamflow deficits. The mapping of SPI-n (SPI accumulation period most strongly correlated
25 with SSI-1) in Fig. 8, identified a strong spatial pattern reflecting the north-west to south-east
26 precipitation and geological gradient found in the UK. Many of those catchments in the south
27 and east where the SPI-n duration is longer are located in regions underlain by major aquifers.
28 In 14 boreholes in England and Wales, Bloomfield and Marchant (2013) found that the
29 Standardised Groundwater Index (SGI) was most strongly correlated to SPI accumulation
30 periods of 6-28 months. The SPI accumulation period most related to the SGI was site specific
31 and related to hydrogeological properties of the aquifers. Similar results were found in southern
32 Germany and central Netherlands (Kumar et al., 2015). Lorenzo-Lacruz et al. (2013b) found

1 SSI-1 was more strongly correlated to SPI-12 in southern Spain, where many catchments have
2 limestone headwaters, contrasting with catchments on less permeable geologies that showed
3 stronger correlations for short SPI accumulation periods. While Vicente-Serrano and López-
4 Moreno (2005) found SPI was strongly correlated to standardised streamflow over
5 accumulation periods of one to three months in a responsive catchment with little storage in the
6 Central Spanish Pyrenees.

7 Figure 9 shows the strong correlations of SSI-1 with a range of SPI accumulation periods.
8 Although, in general, catchments in the south and east can be said to be permeable, there is a
9 range of geologies and not all catchments are highly permeable or are largely influenced by
10 groundwater. In less permeable catchments, the strong correlations at long SPI accumulation
11 periods are likely to be partially a result of the stronger seasonality in the south and east where
12 evapotranspiration is higher (Kay et al., 2013). Where this enhanced seasonality in effective
13 rainfall (precipitation minus evapotranspiration) induces a stronger relationship between
14 streamflow on successive days, autocorrelation in streamflow increases (Chiverton et al.,
15 2015b). This autocorrelation favours the longer SPI accumulation periods.

16 The lagged correlations for the Lambourn, Thet and the Great Stour all show strong correlations
17 across both a range of lags and SPI accumulation periods (Fig. 10) just as lagged correlations
18 of SPI do with the SGI (Bloomfield and Marchant, 2013). While we find (along with Folland
19 et al., 2015) the strongest correlation with streamflow occurs when SPI is not lagged, the
20 presence of strong correlations even at lags of several months (up to six months, in some cases)
21 demonstrates potential for early warning of hydrological drought based on persistence of
22 meteorological anomalies. Indeed, this characteristic is already used for making successful
23 seasonal streamflow forecasts based on persistence in the UK (Svensson, 2014). This
24 forecasting method currently estimates whether flows are likely to be in high, medium or low
25 bins, but the results presented here suggest that further work could focus more specifically on
26 drought indicators. Rivers in the north and west do not benefit from the slow release of stored
27 groundwater; instead, methods that reflect the expected meteorological conditions are needed
28 for making skilful streamflow forecasts (Svensson et al., 2015a). The closeness of the lagged
29 SPI-n duration and the largest lag for which there is significant autocorrelation in SSI-1
30 (autocorrelation max) suggests that lagged SPI-n duration is dependent on the autocorrelation
31 in monthly flows – indeed, lagged SPI-n duration and the autocorrelation max are significantly
32 correlated ($r=0.85$, $\alpha=0.001$).

1 **5.3 Links with climate and catchment properties**

2 Analysis of SAAR and hydrological drought characteristics showed that for upland catchments
3 (clusters one and two), the general precipitation climate (characterised by SAAR) was much
4 more important in influencing hydrological drought characteristics (Table 3) than in lowland
5 catchments (clusters three and four; Table 3, Fig. 12). Table 3 and Fig. 11 also show the strong
6 relationship between SAAR and the hydrological drought characteristics for all catchments
7 together, a result of the prominent precipitation gradient seen between the north-west and the
8 south-east of the UK. Similarly, Haslinger et al. (2014) found that climate was more influential
9 than catchment properties in Austrian catchments where small-scale geological differences
10 could not explain the variation in correlation significance between streamflow and
11 meteorological drought indices across four geologically similar regions. Precipitation was
12 found to be necessary to produce a significant model of median discharge drought duration, in
13 addition to catchment properties for Austrian catchments (Van Loon and Laaha, 2015). A
14 combination of the weather type (based on the objective Grosswetterlagen weather
15 classification) and catchment properties was found to contribute to the hydrological response
16 time in catchments across the UK and Denmark (Fleig et al., 2011). On a broader scale, in a
17 study of 808 near-natural streamflow records in Europe and the USA, Tijdeman et al. (2015)
18 found that climate classification systems that included absolute precipitation were best for
19 differentiating catchments based on hydrological drought duration. In addition, BFI, the
20 seasonality of precipitation and the occurrence of hot summers were important individual
21 controls on hydrological drought duration.

22 For clusters three and four, mainly located in the lowland south and east of the UK, SAAR was
23 weakly correlated to hydrological drought characteristics (Table 3, Fig. 12). A small range of,
24 and generally lower, average annual precipitation, and the presence of permeable aquifer
25 outcrops, means that catchment properties, particularly those related to catchment storage (for
26 example, BFI, percentage of highly productive fractured rock and PROPWET), are more
27 influential than SAAR in determining the drought and propagation characteristics (Fig. 13).
28 Groundwater storage and responsiveness has been found to be important in determining drought
29 duration and severity. In Austrian catchments, Van Loon and Laaha (2015) found that the mean
30 duration of discharge droughts had a strong positive correlation with BFI, as was found in this
31 study for clusters three and four (Fig. 13). Van Loon and Laaha (2015) also found that other
32 catchment properties representative of catchment storage, such as aquifer depth and the

1 presence of lakes and wetlands, had weak correlations with mean discharge drought duration.
2 In the present study, stronger positive correlations were found between drought duration and
3 the percentage of highly productive fractured rock and the percentage of the catchment with no
4 gleyed soils. The weaker relationships in the Austrian study were thought, however, to be a
5 result of missing data for some of the catchment properties, rather than a lack of influence (Van
6 Loon and Laaha, 2015).

7 Laizé and Hannah (2010) found slope, BFIHOST (a measure of catchment responsiveness
8 derived using the HOST (hydrology of soil types) classification; Boorman et al., 1995),
9 percentage of arable land, elevation and bedrock permeability to significantly influence
10 seasonal flows in UK Benchmark catchments. They classified catchments into upland
11 impermeable, lowland permeable and lowland impermeable groups. In lowland permeable
12 catchments, regional climate was a poorer predictor of streamflow due to the climate buffering
13 provided by the permeable catchment. Chiverton et al. (2015a) found that BFIHOST, the
14 percentage of highly productive fractured rock, the depth to the gleyed soil layer, the percentage
15 of arable land, slope and PROPWET were all significant catchment properties influencing the
16 temporal dependence of flows in UK Benchmark catchments. Temporal dependence can be
17 thought of as indicative of the average lag between meteorological and hydrological signals;
18 catchments in clusters one and two (three and four) showed less (more) temporal dependence
19 in streamflow (Chiverton et al., 2015a). A similar pattern was found here in the SPI-n duration,
20 with shorter (longer) SPI accumulation periods being most strongly correlated in clusters one
21 and two (clusters three and four).

22 Chiverton et al. (2015a) found the percentage of arable land to be the best catchment property
23 to distinguish clusters based on the temporal dependence of streamflow. However, they argued
24 that this was likely due to the positive relationship with the percentage of highly productive
25 fractured rock and the negative relationship with other catchment properties such as high
26 elevations and PROPWET. Arable land, in effect, characterises permeable, lowland well-
27 drained catchments with high storage. In Austrian catchments, forest cover was positively, but
28 weakly, correlated to both discharge drought mean duration and mean deficit (Van Loon and
29 Laaha, 2015). In the present study, the percentage of woodland was significantly ($\alpha=0.1$),
30 although weakly, correlated to the percentage of no gleyed soils, BFI, the percentage of highly
31 productive fractured rock and area ($r= -0.37, -0.37, -0.33, -0.28$, respectively). As such, it is
32 more likely that the significant relationships between the percentage of woodland and

1 hydrological drought characteristics are a result of the soil and geology types associated with
2 the woodland land cover rather than the presence (or absence) of woodland itself.

3 **5.4 Implications for drought monitoring and early warning**

4 The SPI is widely used in existing drought M&EW systems, but the SSI is less widely adopted
5 (Bachmair et al., 2015b). This may be a result of the poorer availability of streamflow data in
6 comparison to precipitation data, especially at the short time scales involved in producing useful
7 drought M&EW products. However, the monitoring of hydrological variables and the
8 incorporation of hydrological drought indices is beneficial for effective drought planning and
9 management, and it is particularly useful for communication purposes if both precipitation and
10 streamflow are monitored in a comparable way. In locations where streamflow data is available,
11 the SSI can be used directly in drought M&EW. While this is preferable, SPI could potentially
12 provide a surrogate for hydrological impacts, provided appropriate response times are known.

13 The correlation results, Fig. 8, showing the spatial variability in SPI-n (accumulation period of
14 SPI most strongly correlated with SSI-1), give an indication of accumulation periods that could
15 stand as proxies for hydrological droughts in monthly precipitation data. This allows the more
16 widely and rapidly available precipitation data to be used for identifying future potential
17 hydrological droughts. The identification of these relationships could also allow estimation in
18 areas where no streamflow data exist, based on precipitation data; the most suitable timescales
19 for monitoring could be estimated based on widely available climate and catchment descriptors
20 (in particular SAAR and BFIHOST which are available at ungauged locations; Spackman,
21 1993; Boorman et al., 1995; Bayliss, 1999).

22 The results also highlight some of the problems with using the SPI and SSI when calculated for
23 long accumulation periods for locations that have seen an increasing, or decreasing, long-term
24 trend in precipitation or streamflow such as Scotland. Although being able to calculate SPI or
25 SSI for any user-defined accumulation period makes the indicators more flexible, it is essential
26 that meaningful accumulation periods should be chosen to capture the drought characteristics
27 typical of current meteorological or hydrological conditions (Vicente-Serrano and López-
28 Moreno, 2005). For example, the long, severe droughts shown in Scotland for both SPI and SSI
29 for the 18-month accumulation period (Fig. 3 and Fig. 5) are not typical of the droughts that
30 have been observed (Jones and Lister, 1998; Marsh et al., 2007). The short droughts that have
31 been most influential for water resources in Scotland are better captured by shorter

1 accumulation periods that are less confounded by the long-term increased precipitation and
2 streamflow trends. Moreover, the findings reaffirm that accumulation periods should be chosen
3 based on likely impacts; Bachmair et al. (2015a) observed that short SPI periods are strongly
4 linked to impacts in northwest Britain while longer SPI periods trigger impacts in the southeast.

5 **5.5 Further research**

6 With the importance of groundwater, particularly in the south and east of England for water
7 supply, to understand fully hydrological drought characteristics and propagation, it is necessary
8 to include a groundwater component to the analysis. Furthermore, although catchment storage
9 plays a key role in determining hydrological drought characteristics and propagation in the
10 south and east, the seasonality and autocorrelation of streamflow, caused by of
11 evapotranspiration, will also be influential. Undertaking propagation analysis though the
12 hydrological cycle, using the Standardised Precipitation Evapotranspiration Index (SPEI;
13 Vicente-Serrano et al., 2010), the Standardised Streamflow Index (SSI; Vicente-Serrano et al.,
14 2012b; Lorenzo-Lacruz et al., 2013a) and the Standardised Groundwater Index (SGI;
15 Bloomfield and Marchant, 2013) would therefore give a clearer picture of the climate and
16 catchment properties influential on drought duration, severity and propagation, paving the way
17 for more integrated drought M&EW. In addition the seasonal variability in drought propagation
18 should be investigated. Studies in Spain found there were distinct differences between the
19 duration of the SPI and SPEI) accumulation period most strongly correlated with standardised
20 monthly streamflow (SSI-1) depending on whether full time-series or individual months were
21 cross-correlated (Vicente-Serrano and López-Moreno, 2005; López-Moreno et al., 2013). The
22 seasonal component is particularly important in the south and east of England where summer
23 streamflow and water resources are highly dependent on winter recharge.

24 The use of near-natural Benchmark catchments in this study has allowed the investigation of
25 hydrological drought characteristics and propagation processes without results being
26 confounded by artificial influences. However, it is often man-made systems that the human
27 population is most reliant upon for water supply, agriculture etc. Understanding these processes
28 in catchments affected by anthropogenic activities is crucial for truly effective drought M&EW
29 systems. Further work on the drought and propagation characteristics in these modified systems
30 will be much more challenging (Van Loon, 2015). It is likely that the combination of human
31 activities, alongside natural catchment and climate characteristics, will produce more divergent
32 results. However, the results from this study could be used to stratify catchments based on their

1 climate and catchment properties when tackling the challenges of quantifying drought hazard
2 in catchments with anthropogenic modifications.

3 Finally, as with most observation-based studies of drought, the brevity of available hydrological
4 records is a constraint. The period of analysis (1961-2012) does not capture the full range of
5 known hydrological variability, and previous studies have highlighted the importance of earlier
6 droughts in the UK (Marsh et al., 2007). Longer records could influence the drought
7 characteristics presented here, although the same regional picture and propagation
8 characteristics would undoubtedly emerge. Similar methods to those used here will be applied
9 in the future to longer records. Localised reconstructions of drought are becoming available
10 (Lennard et al., 2015; Spraggs et al., 2015) while national-scale reconstruction research is in
11 progress (e.g. Historic Droughts; <http://www.ceh.ac.uk/our-science/projects/historic-droughts>).

12 **6 Conclusion**

13 Meteorological and hydrological drought characteristics and propagation behaviours of 121
14 near-natural UK catchments were analysed using SPI and SSI over a range of accumulation
15 periods. Meteorological drought duration and severity characteristics showed little spatial
16 variability, whilst hydrological drought characteristics showed many (few), short (long), less
17 (more) severe events in the north and west (south and east) of the UK. Catchments underlain
18 by aquifers tended to show more of a delay in the propagation of drought from meteorological
19 to hydrological drought, with longer SPI accumulation periods most strongly correlated with
20 SSI-1. Standard-period average annual rainfall was found to be important for drought duration,
21 severity and propagation in the north and west of the UK where catchment storage is generally
22 low, whilst in the south and east, catchment storage and other catchment properties are more
23 influential on drought duration, severity and propagation. The greater understanding of the UK
24 drought hazard provided by this study can be used as a foundation for future developments of
25 M&EW in the UK, laying the foundations for better drought preparedness and increased
26 resilience to drought.

27 **Acknowledgements**

28 This study is an outcome of the Belmont Forum Project DrIVER (Drought Impacts:
29 Vulnerability Thresholds in monitoring and Early warning Research). Financial support was
30 provided by the UK Natural Environment Research Council (Grant NE/L010038/1). We thank
31 the UK National River Flow Archive (NRFA) for all streamflow and precipitation data, and
32 both the NRFA and the British Geological Survey for catchment property data. The streamflow

1 and precipitation data used here can be obtained from the NRFA on request, as can the majority
2 of catchment properties. The authors would like to thank Sergio Vicente-Serrano, an
3 anonymous reviewer and the editor, Jean-Philippe Vidal, for their constructive comments that
4 helped improve the paper.
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1 Table 1. Summary of catchment properties used (after Chiverton et al., 2015a).

Catchment Property	Abbreviation	Units	Description
Altitude	Alt	m	Altitude of the gauging station to the nearest datum ¹ (derived using IHDTM ²).
Elevation 10	Elev-10	m	Height above the datum ¹ below which 10% of the catchment lies (derived using IHDTM ²).
Elevation 50	Elev-50	m	As above but for 50%.
Elevation 90	Elev-90	m	As above but for 90%.
Elevation max	Elev-max	m	As above but for the maximum value
Woodland	Wood	%	Amount of the catchment covered by woodland calculated from the CEH land cover maps 2000. This is an aggregation of broad-leaved/mixed woodland and coniferous woodland.
Arable land	Arable	%	As above but using an aggregation of: arable cereals, arable horticulture and arable non-rotational.
Grassland	Grass	%	As above but using an aggregation of: improved grassland, neutral grassland, set-aside grassland, bracken, calcareous grassland, acid grassland and fen, marsh and swamp.
Mountain, Heathland and Bog	MHB	%	As above but an aggregation of: dense dwarf shrub heath, open dwarf shrub heath, bog (deep peat), montane habitats and inland bare ground.
Urban extent	Urban	%	As above but using an aggregation of: suburban, urban and inland bare ground.
Area	N/A	km ²	Catchment area calculated using the IHDTM ² .
Drainage Path Slope _(FEH³)	Slope	m km ⁻¹	Mean drainage path slope calculated from the mean of all inter-nodal slopes (derived using IHDTM ²).

Catchment Property	Abbreviation	Units	Description
PROPWET _(FEH³)	PROPWET	%	Proportion of time soils are wet (defined as a soil moisture deficit of less than 6mm).
FARL _(FEH³)	FARL	Ratio	Flood attenuation attributed to reservoirs and lakes.
Base flow index	BFI	Ratio	Calculated from mean daily flow using the method outlined in Gustard et al. (1992).
No gleyed soils	S-no	%	Percentage of the catchment made up of HOST ⁴ classes with no gleying: 1-8, 16 and 17.
Deep gleyed soils	S-deep	%	Percentage of the catchment made up of HOST ⁴ classes with gleying between 40 and 100cm: 13 and 18-23.
Shallow gleyed soils	S-shallow	%	Percentage of the catchment made up of HOST ⁴ classes with gleying within 40cm: 9, 10, 14, 24 and 25.
Peat soils	Peat	%	Percentage of the catchment made up of HOST ⁴ classes: 11, 12, 15, 36 and 29.
Fracture high	F-high	%	Percentage of the catchment underlain by highly productive fractured rocks.
Fracture medium	F-med	%	Percentage of the catchment underlain by moderately productive fractured rocks.
Fracture low	F-low	%	Percentage of the catchment underlain by low productivity fractured rocks.
Intergranular high	I-high	%	Percentage of the catchment underlain by highly productive intergranular rocks.
Intergranular medium	I-med	%	Percentage of the catchment underlain by moderately productive intergranular rocks.
Intergranular low	I-low	%	Percentage of the catchment underlain by low productivity intergranular rocks.

Catchment Property	Abbreviation	Units	Description
No groundwater	no-GW	%	Percentage of the catchment underlain by rocks classed as having essentially no groundwater.

- 1 ¹Datum refers to Ordnance Datum, or in Northern Ireland, Malin Head Datum.
- 2 ²IHDTM refers to the Integrated Hydrological Digital Terrain Model (Morris and Flavin, 1990).
- 3 ³FEH refers to catchment properties described in the Flood Estimation Handbook (Bayliss, 1995).
- 4 ⁴HOST refers to the hydrology of soil types classification (Boorman et al., 1995).
- 5

1 Table 2. Median drought characteristics calculated for selected SPI and SSI accumulation
 2 periods using thresholds of -1, -1.5 and -2 for all catchments.

Threshold	SPI/SSI Accumulation Period (months)	Total Number of Events	Duration (months)			Severity (-)			
			Mean	Median	Max.	Mean	Median	Max.	
SPI	-1	1	68	2.56	2	8	-2.68	-2.29	-8.33
		6	20	9.72	8	24	-9.69	-6.91	-30.88
		18	7	26.86	23	53	-26.86	-21.47	-56.77
	-1.5	1	36	2.75	2	7	-3.29	-2.83	-8.33
		6	12	11.54	10	24	-12.61	-10.44	-30.88
		18	5	30.20	27	53	-33.34	-29.11	-56.77
	-2	1	14	2.88	2.5	7	-3.89	-3.53	-7.39
		6	6	13.20	12	24	-16.45	-14.33	-30.88
		18	3	32.25	31	47	-40.81	-36.76	-56.15
SSI	-1	1	42	3.81	3	13	-3.95	-3.10	-16.84
		6	15	12.06	10	27	-11.86	-8.96	-35.82
		18	6	31.00	27	53	-31.35	-25.74	-57.79
	-1.5	1	22	4.69	4	13	-5.39	-4.22	-16.84
		6	9	14.80	14	28	-16.60	-14.29	-35.93
		18	4	33.00	29.5	53	-36.20	-32.03	-58.32
	-2	1	7	5.75	5	12	-7.64	-5.93	-16.84
		6	4	18.00	17	27	-23.32	-22.38	-35.58
		18	2	34.83	34	45	-44.88	-44.00	-53.78

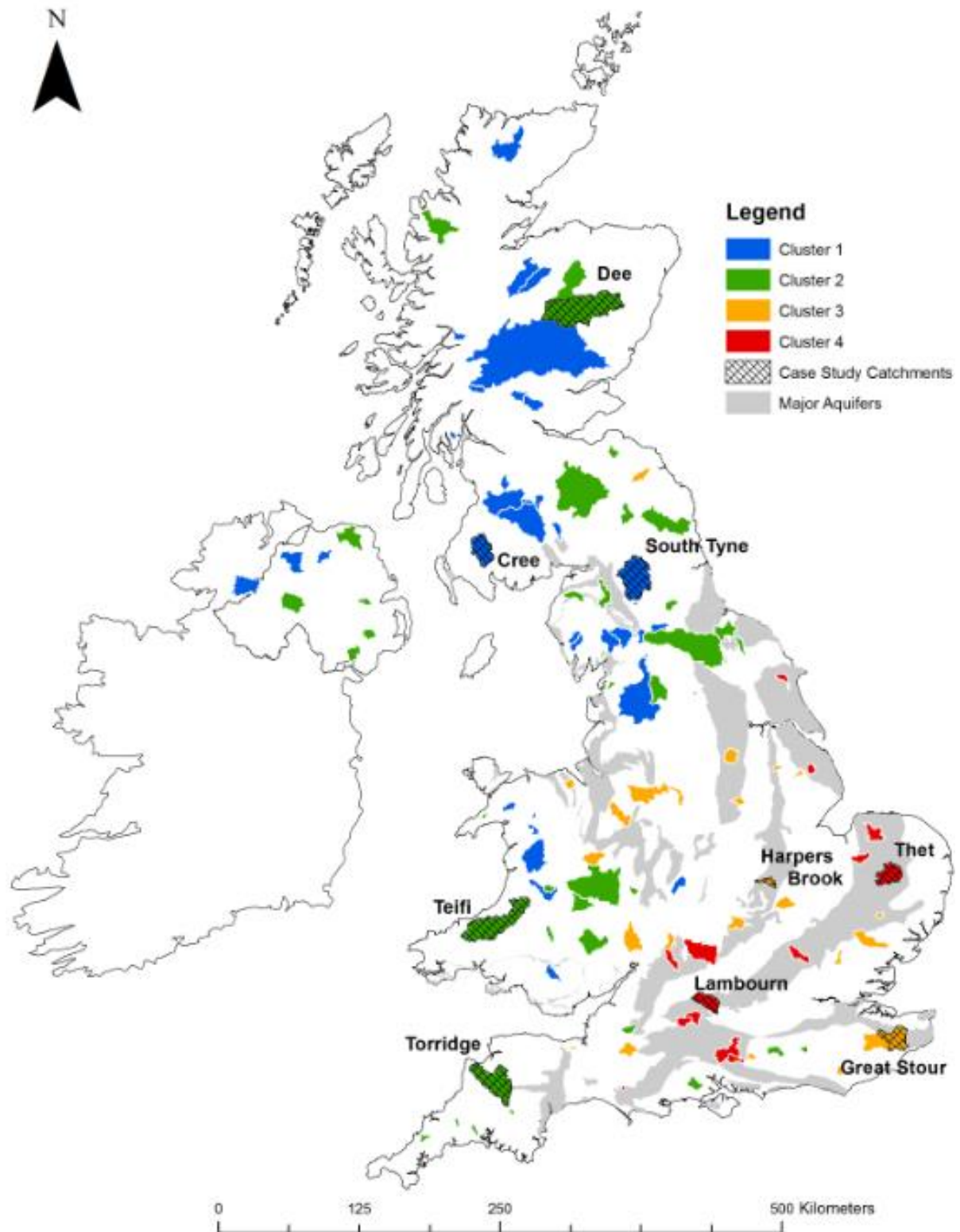
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4

1 Table 3. Correlation coefficients for Spearman correlations between hydrological drought
 2 characteristics and SAAR (* $\alpha = 0.1$; ** $\alpha = 0.01$; *** $\alpha < 0.001$). Drought characteristics
 3 calculated using SSI-1 and a threshold of -1.

Drought Characteristic	Clusters 1 & 2	Clusters 3 & 4	All Catchments
Total Number of events	0.47***	0.12	0.76***
Median Duration (months)	-0.52***	-0.14	-0.77***
Maximum Duration (months)	-0.57***	-0.25	-0.78***
Median Severity (-)	0.54***	0.08	0.76***
Max Severity (-)	0.60***	0.14	0.81***
SPI-n Duration (months)	-0.51***	0.00	-0.76***
SPI-n r value	0.68***	0.26	0.69***

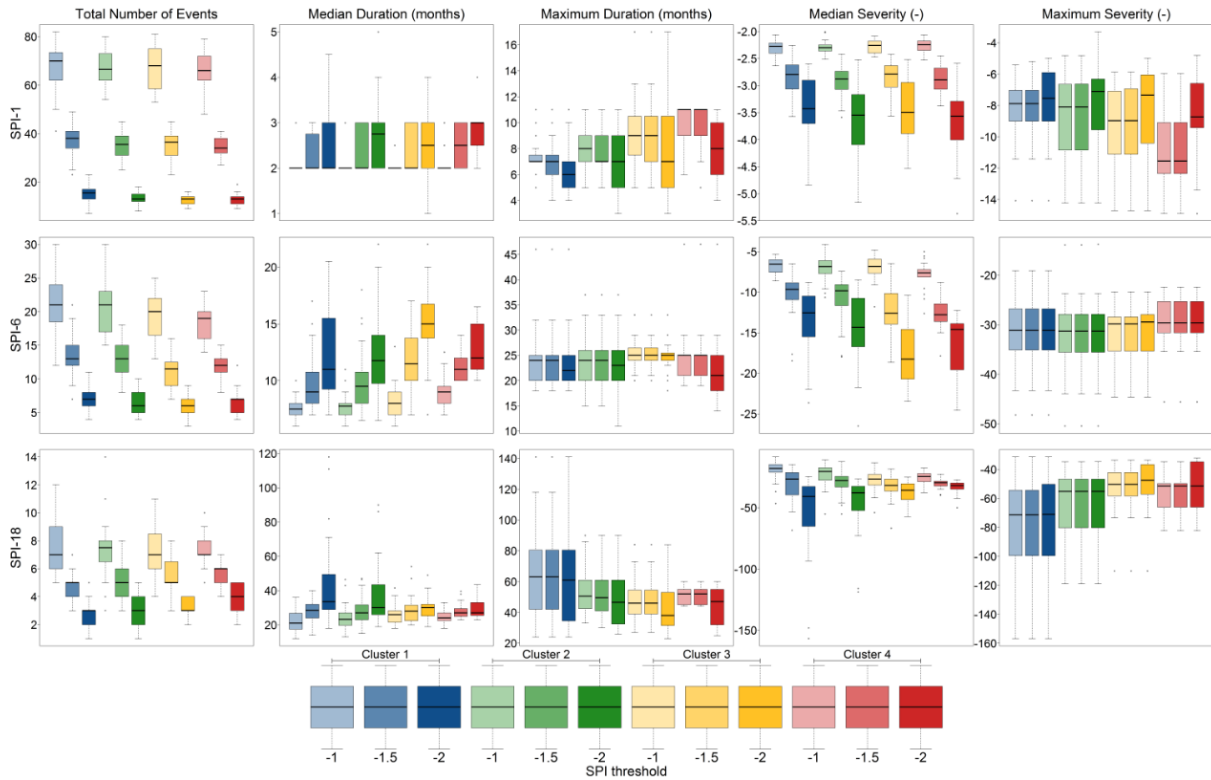
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2 Figure 1. Location and cluster membership of UK Benchmark catchments selected for this study
 3 including the nine case study catchments.

1

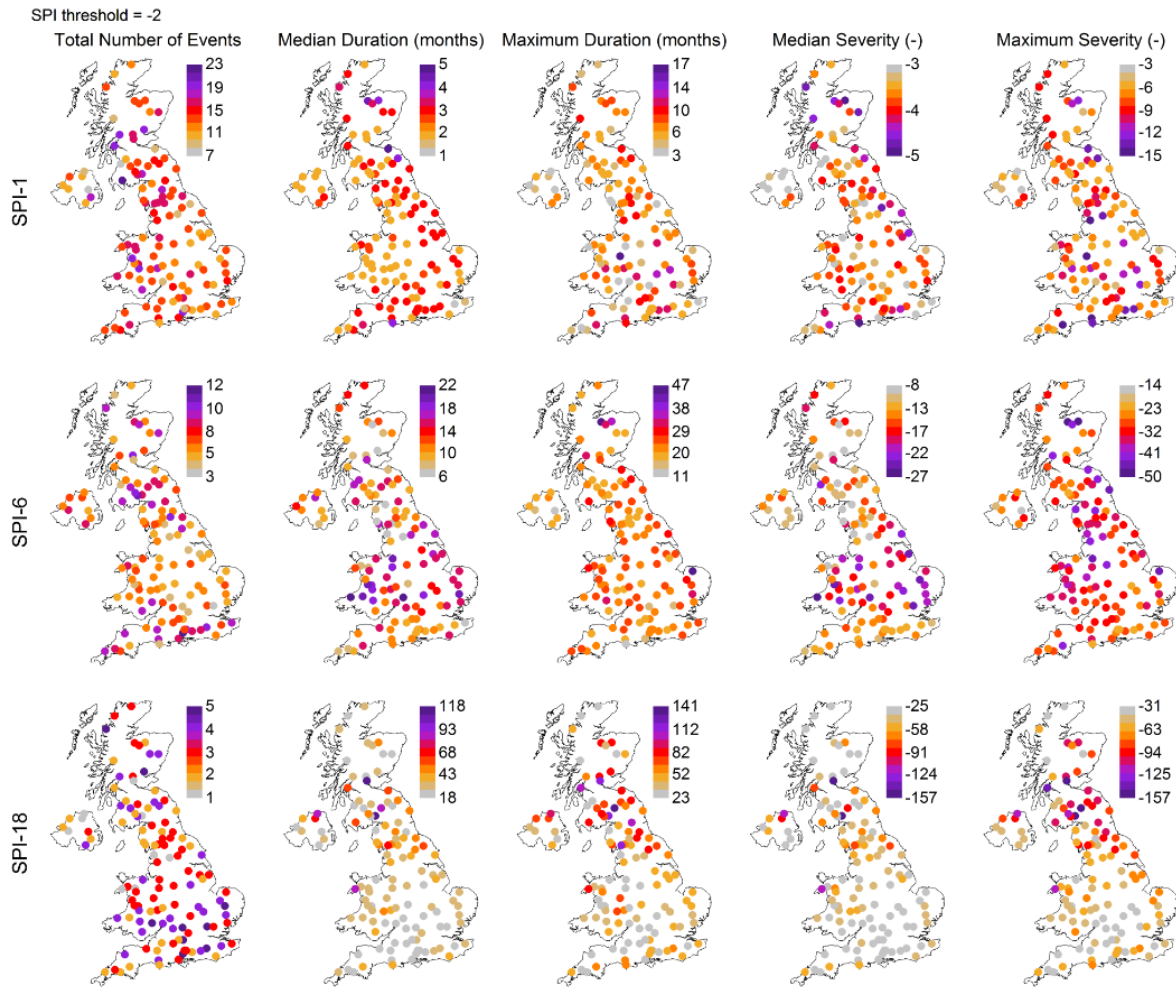


2

3 Figure 2. Boxplots showing meteorological drought characteristics based on SPI using
4 thresholds of -1, -1.5 and -2 for each cluster. Note that the y-axis scale is different for each
5 accumulation period to best show the full variability of the results.

6

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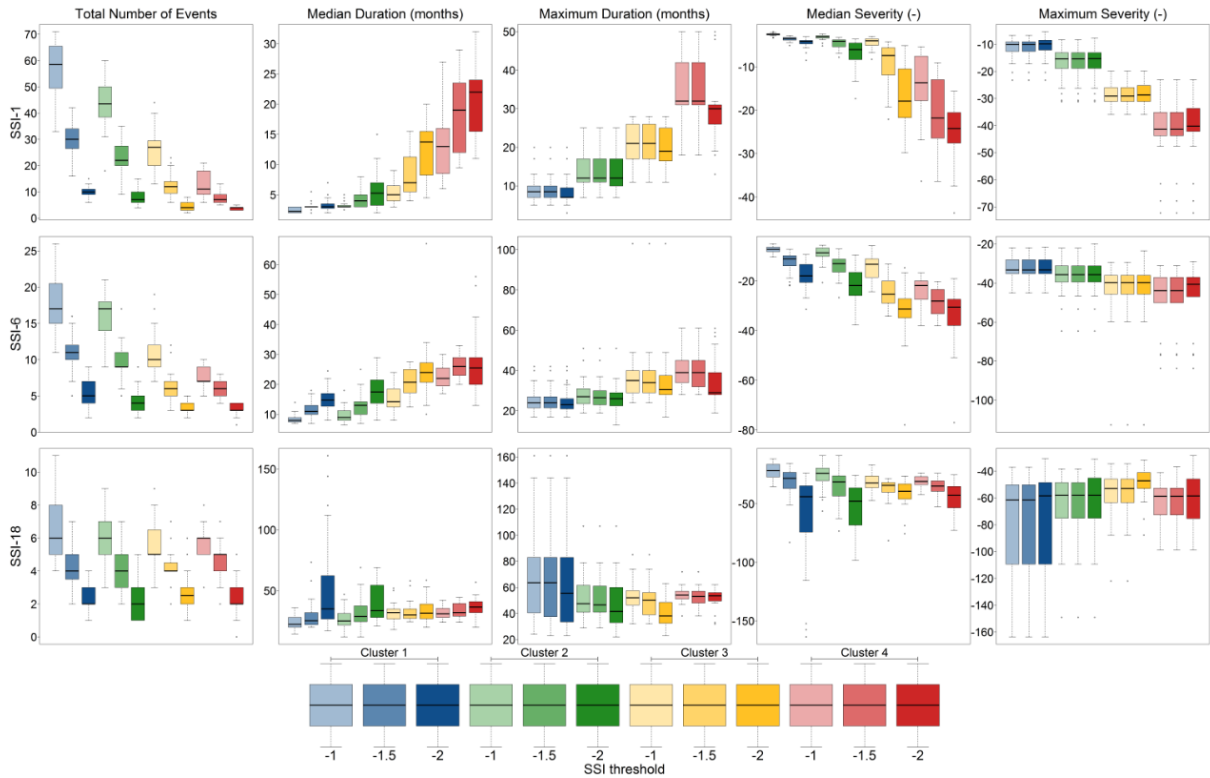


2

3 Figure 3. Maps showing selected meteorological drought characteristics based on SPI-1, SPI-6
4 and SPI-18 using a threshold of -2. Note that the colour scale is different for each accumulation
5 period to best show the spatial variability of the results.

6

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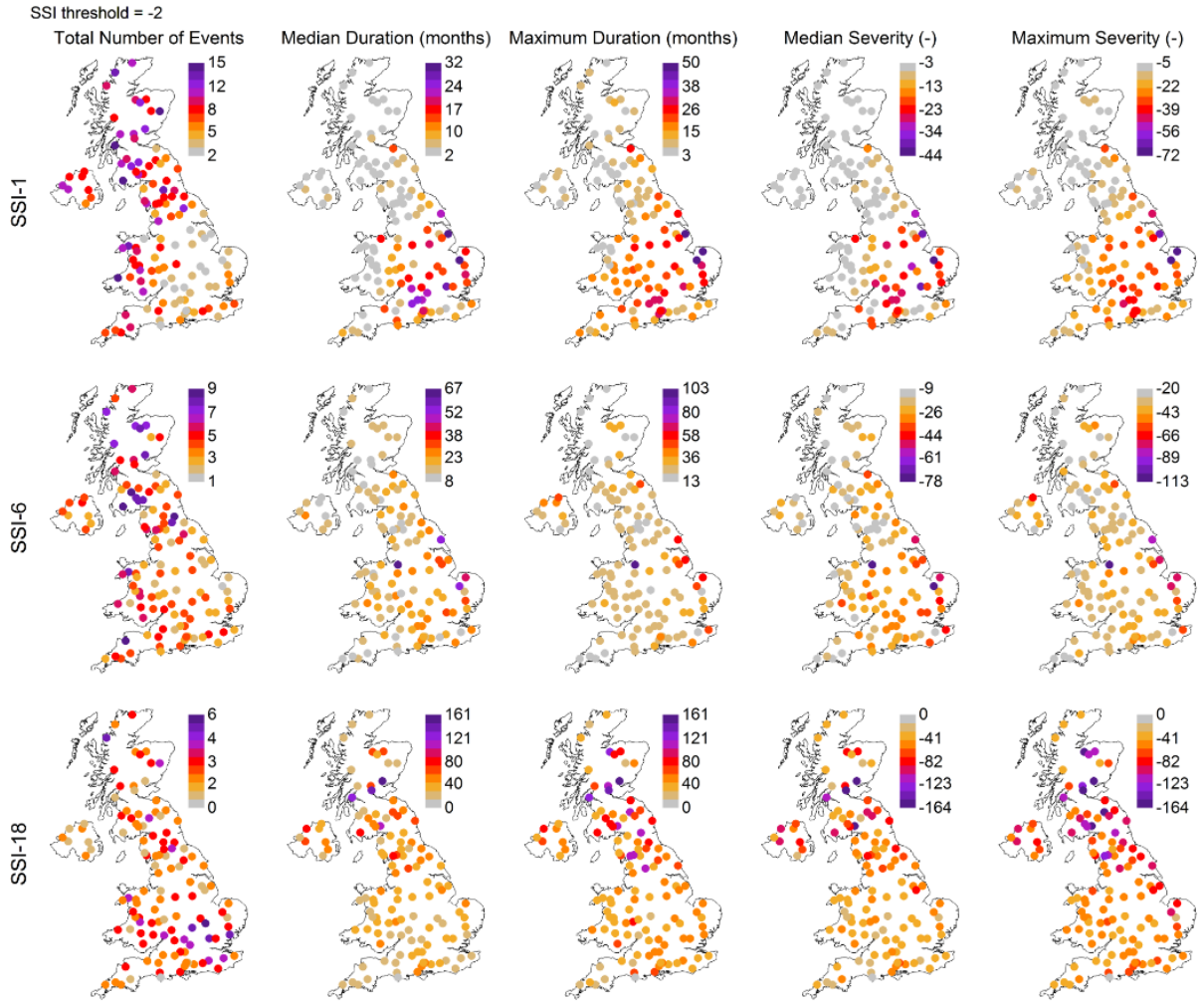


2

3 Figure 4. Boxplots showing hydrological drought characteristics based on SSI using thresholds
4 of -1, -1.5 and -2 for each cluster. Note that the y-axis scale is different for each accumulation
5 period to best show the full variability of the results.

6

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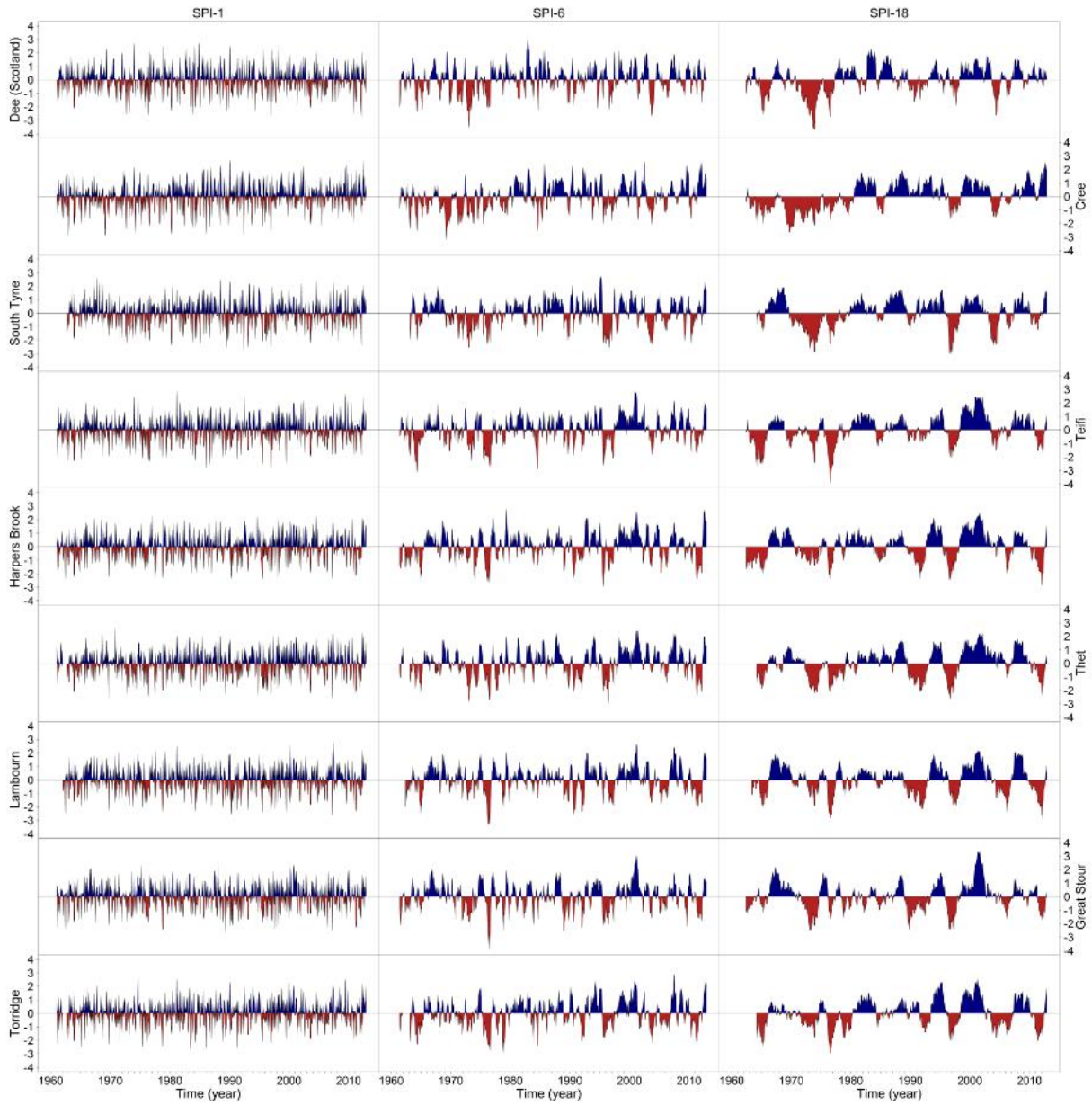


2

3 Figure 5. Maps showing selected hydrological drought characteristics based on SSI-1, SSI-6
4 and SSI-18 using a threshold of -2. Note that the colour scale is different for each accumulation
5 period to best show the spatial variability of the results.

6

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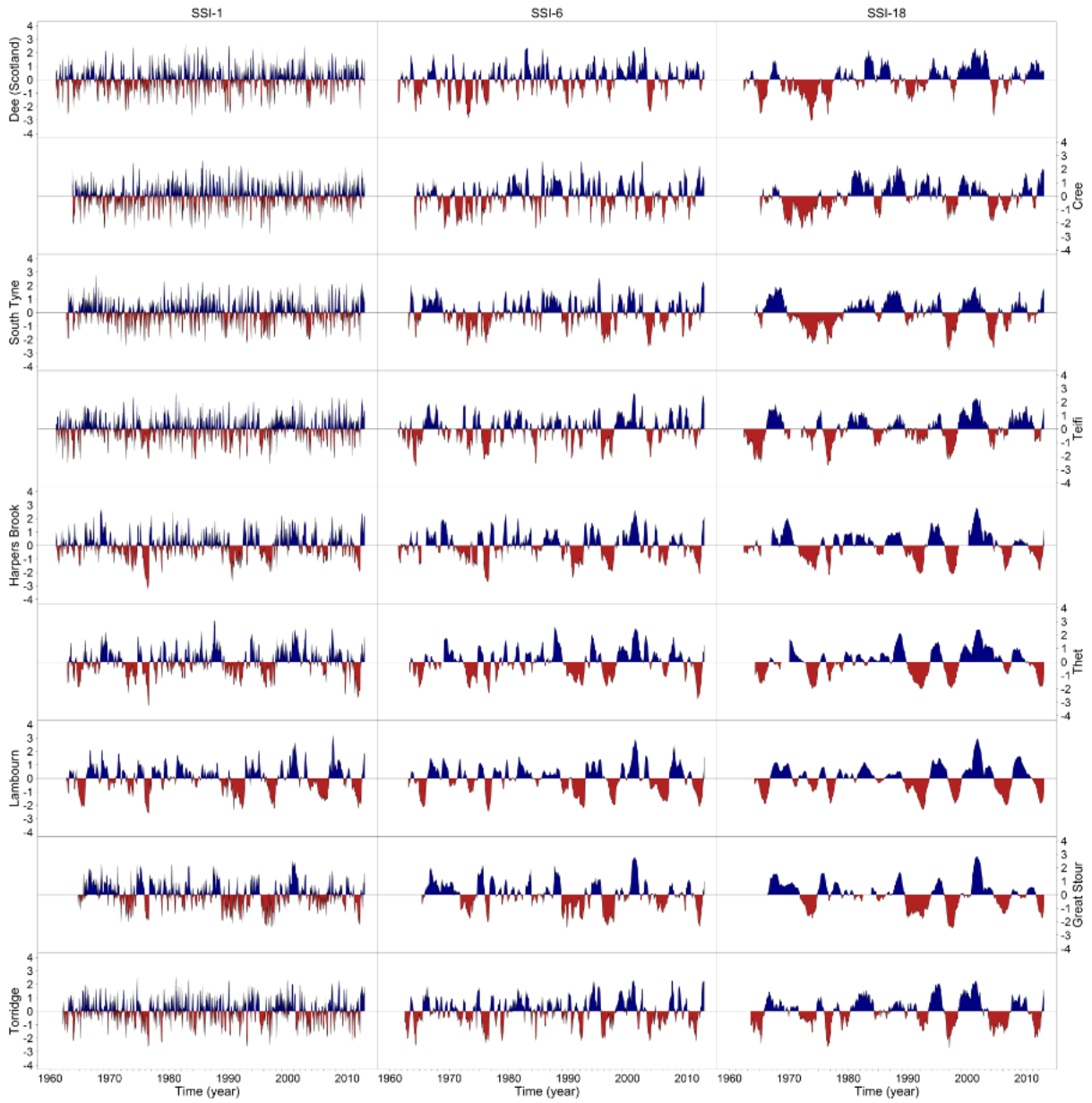


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3 Figure 6. Case study catchment SPI time series for selected accumulation periods.

4

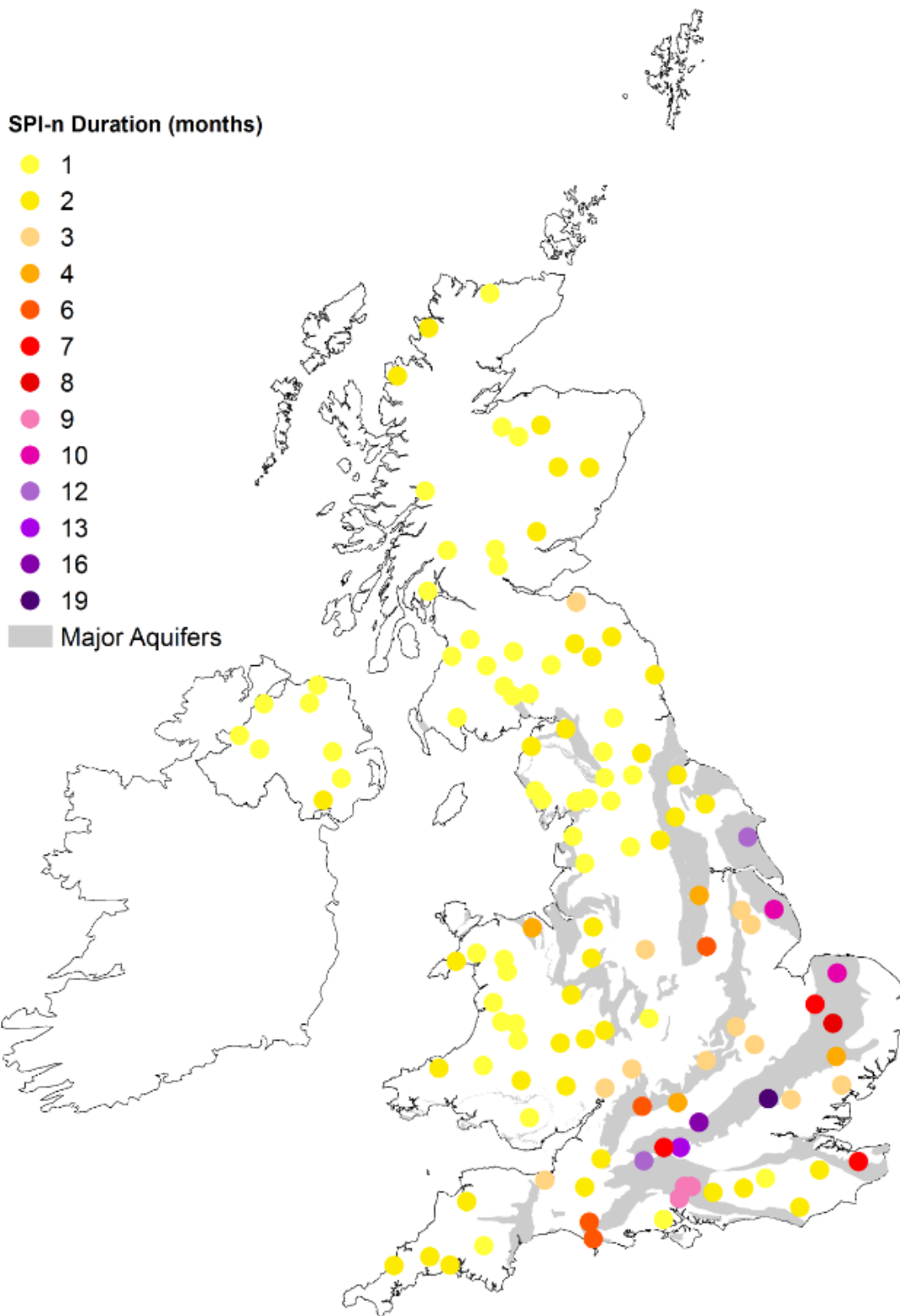
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3 Figure 7. Case study catchment SSI time series for selected accumulation periods.

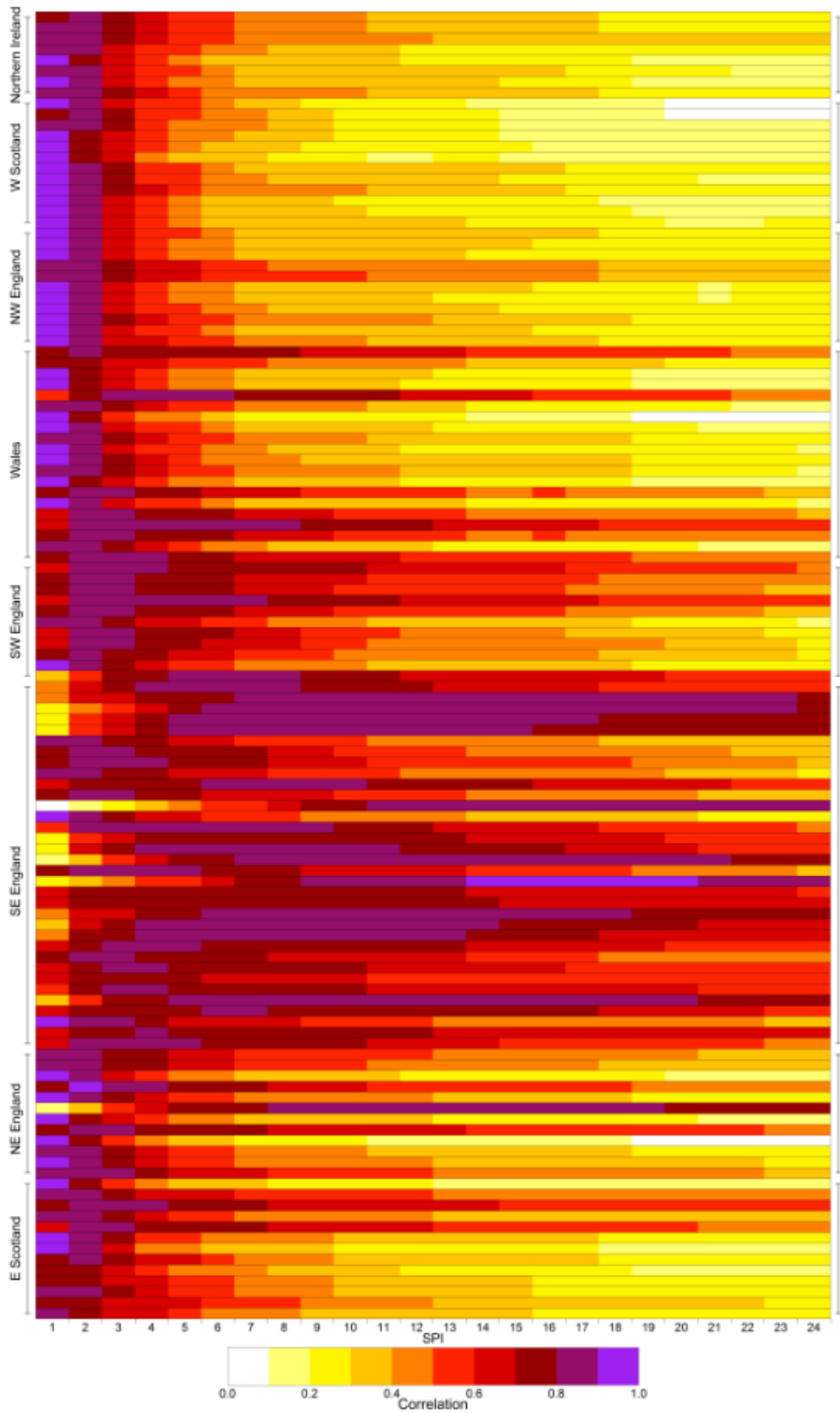
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1

2 Figure 8. Map of catchments showing the SPI accumulation period most strongly correlated
 3 with SSI-1 (SPI-n) and the location of major UK aquifers.

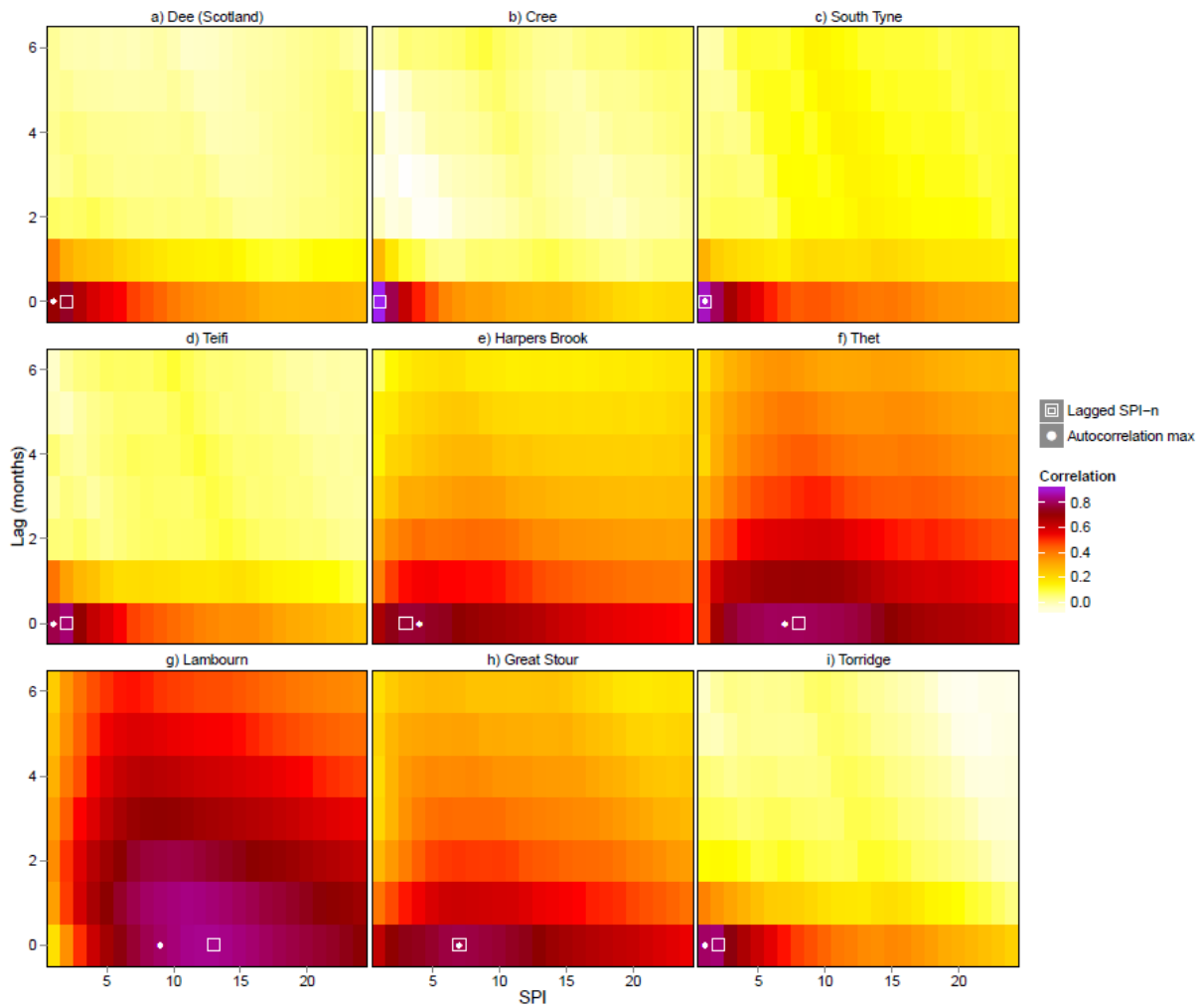
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1

1 Figure 9. Heatmap showing correlations of SPI accumulation periods of 1-24 months with SSI-
2 1 for all catchments.

3

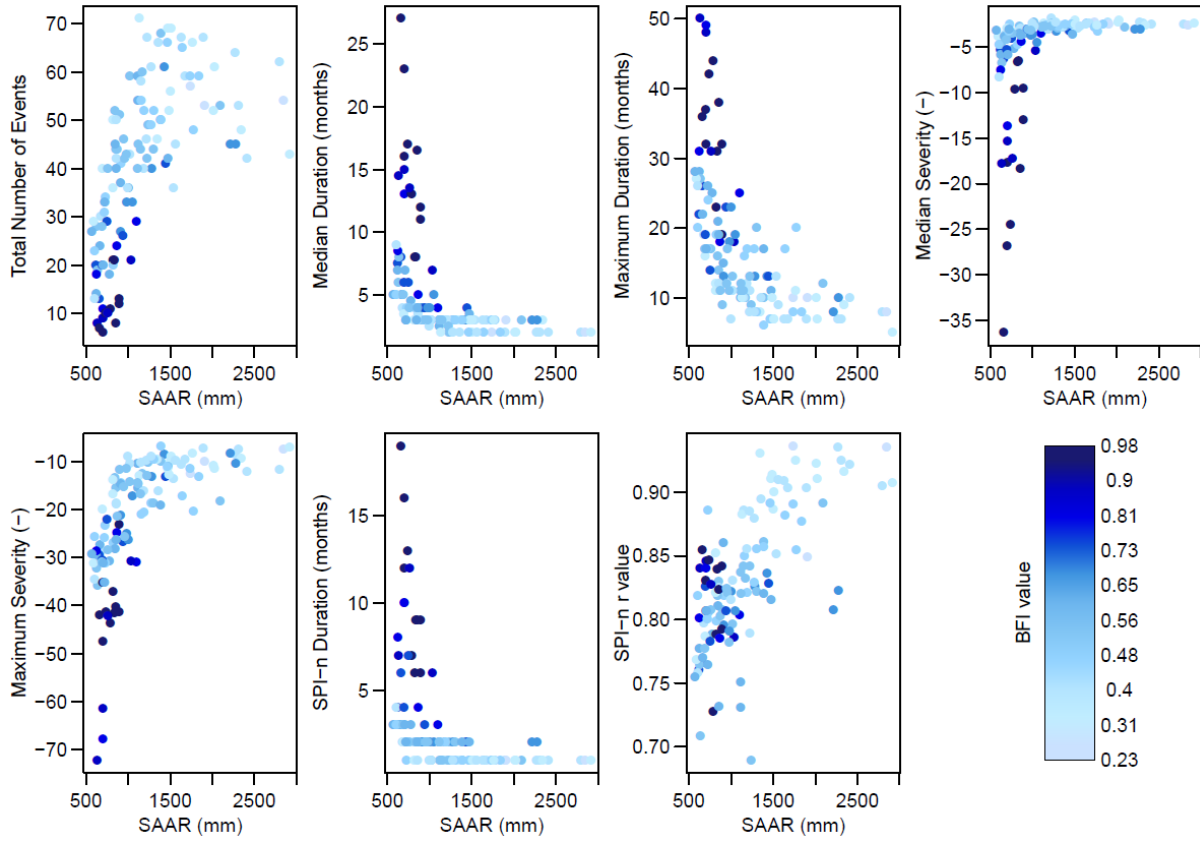


4

5 Figure 10. Heatmaps for case study catchments showing correlation between SSI-1 lagged by
6 0-6 months and SPI accumulation periods of 1-24 months. The lagged SPI-n is shown, as is the
7 longest n-month period for which there is significant autocorrelation in SSI-1 (autocorrelation
8 max).

9

1

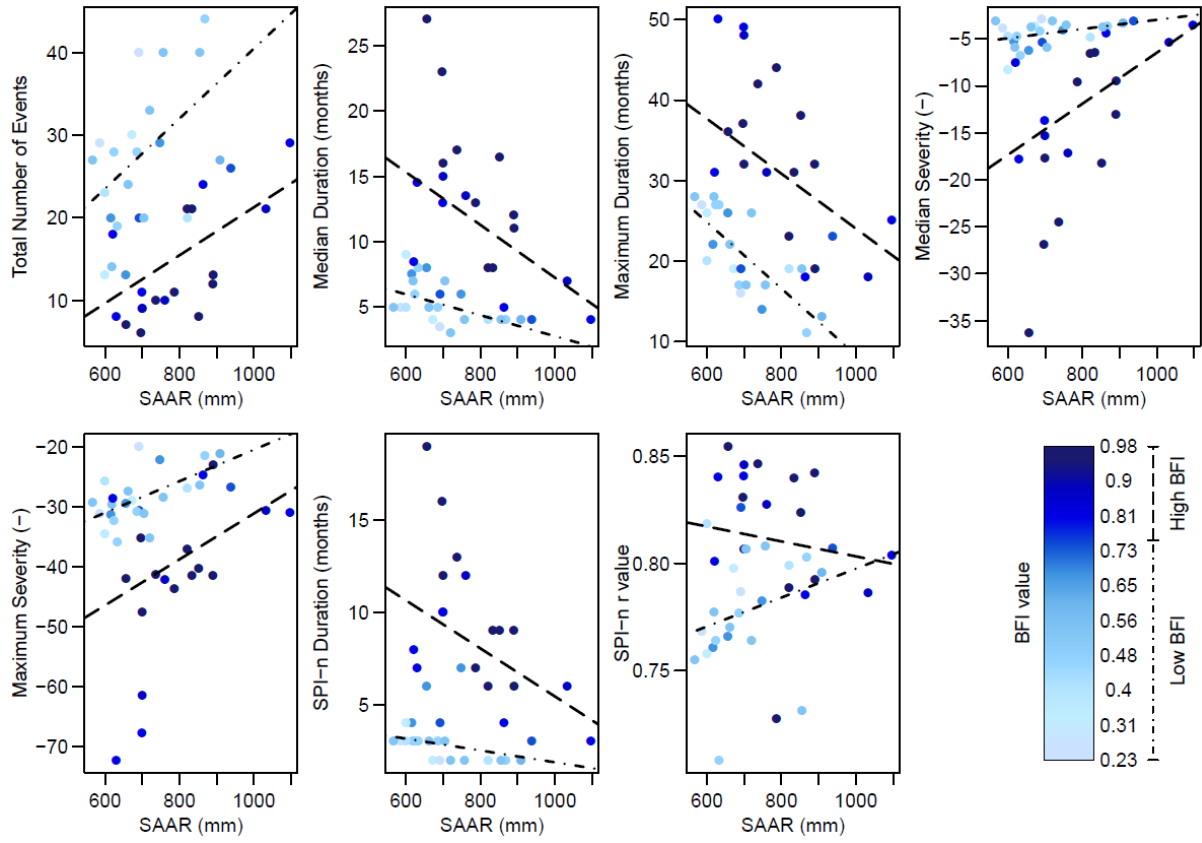


2

3 Figure 11. Relationship between hydrological drought characteristics based on SSI-1 using a
4 threshold of -1 and SAAR for all catchments.

5

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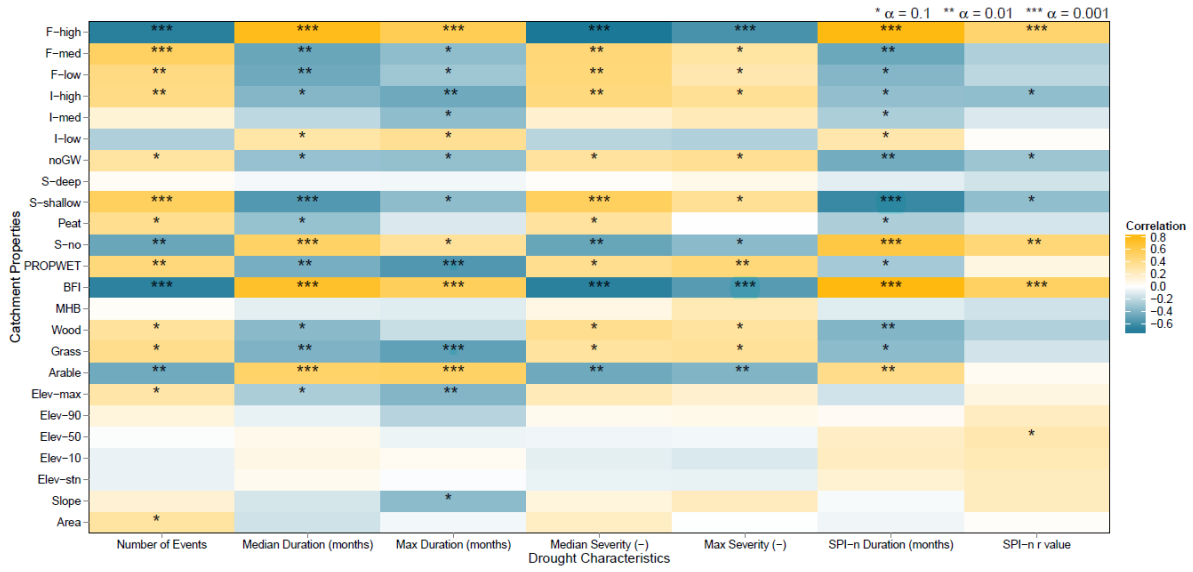


2

3 Figure 12. Relationship between hydrological drought characteristics based on SSI-1 using a
4 threshold of -1 and SAAR for catchments in clusters three and four.

5

1



2

3 Figure 13. Heat map showing the correlations between selected hydrological drought
 4 characteristics based on SSI-1 using a threshold of -1 and catchment properties for catchments
 5 in clusters three and four. See Table 1 for descriptions of the catchment properties.

6