Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2015-476, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 15 January 2016


Hydrology and Earth System Sciences
Discussions
Open Access



# A systematic assessment of drought termination in the United Kingdom

**S. Parry[1,2], R. L. Wilby[2], C. Prudhomme[1,2], and P. J. Wood[2]**

[1]Centre for Ecology and Hydrology, Maclean Building, Benson Lane, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB, UK
[2]Department of Geography, Martin Hall Building, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK

Received: 20 November 2015 – Accepted: 2 December 2015 – Published: 15 January 2016

Correspondence to: S. Parry (spar@ceh.ac.uk)

Published by Copernicus Publications on behalf of the European Geosciences Union.

## Abstract

Drought termination can be associated with dramatic transitions from drought to storms and flooding, and this is certainly true for recent events in the United Kingdom (UK). Attention devoted to these newsworthy and memorable events may be at the expense of drought terminations that proceed gradually and pose a different set of challenges for water resource managers. This paper defines drought termination as a phase of drought in its own right and makes the case for a more systematic approach to its identification and characterisation, applying an objective approach to detect drought terminations in observed river flow records for 52 catchments. The resulting archive of 459 drought terminations provides an unprecedented historical perspective on drought termination in the UK. Nationally- and regionally-coherent drought termination events are identifiable, although drought termination characteristics vary both between and within major episodes. Contrasting drought termination events in 1995–1998 and 2009–2012 are described in greater depth. The dataset is also used to assess potential linkages between metrics of drought termination characteristics and catchment properties. The duration of drought termination is moderately negatively correlated with elevation and catchment average rainfall, suggesting that wetter catchments in upland areas of the UK tend to experience shorter drought terminations. More urbanised catchments have a tendency for gradual drought terminations, contrary to perceptions of flashy hydrological response in these areas, although this may also be related to the type of catchments typical of lowland England. Potential linkages are found between both the duration and rate of drought termination and the duration of the preceding drought development phase, which may have important implications for water resources management during a drought. The dataset helps to place individual events within a long-term context. The drought termination phase in 2009–2012 was, at the time, regarded as exceptional in terms of magnitude and spatial footprint but the Thames river flow record reveals comparable events before 1930. Hence, the approach adopted and the chronologies of drought termination enable objective intercomparison of events. The dataset may





HESSD

doi:10.5194/hess-2015-476

in due course provide a basis for better understanding the drivers, long-term trends in occurrence and characteristics, and impacts of historical and contemporary drought termination events.

## 1 Introduction

Drought termination, generally defined as the end of a drought, has often been associated with violent weather conditions and flooding, including in Colorado (Lavers and Villarini, 2013), Pakistan (Webster et al., 2011), China (Lam et al., 2012) and Australia (Leblanc et al., 2009). The UK also experienced notable drought terminations in August–September 1976 (Doornkamp et al., 1980) and in April–July 2012 (Parry et al., 2013). Notwithstanding these examples, drought termination events have been relatively neglected by drought research. Studies which address this phenomenon have focused on extreme transitions at the end of a drought (e.g. Yang et al., 2012; Ning et al., 2013). Such events are more newsworthy and damaging, but there has been a lack of attention devoted to assessing the full range of drought termination types and characteristics. Whilst abrupt drought terminations may result in destructive impacts, gradual drought terminations may be problematic for water resource managers who must reconcile public relations with continued water restrictions during wet weather.

Some studies systematically identify and characterise droughts themselves (e.g. Hisdal et al., 2001; Pfister et al., 2006; Marsh et al., 2007; Fleig et al., 2011; Li et al., 2013), but these have generally not considered the drought termination phase. A limited historical perspective can be gained from studies of drought termination on an event basis, including those based on hydrometeorological (e.g. Kienzle, 2006; Marengo et al., 2008), remotely sensed (e.g. Wang et al., 2013; Chew and Small, 2014) or experimental catchment data (e.g. Miller et al., 1997; Lange and Haensler, 2012). Even considering several events is too limited a sample to generalise (e.g. Eltahir and Yeh, 1999; Shukla et al., 2011) or move beyond qualitative descriptions (e.g. Parry et al., 2013). A





HESSD
doi:10.5194/hess-2015-476

systematic assessment of drought termination would enable a more robust analysis of its spatial and temporal variability.

Studies that systematically identify drought termination in the historical record (e.g. Mo, 2011; Kam et al., 2013; Maxwell et al., 2013; Patterson et al., 2013) have typically considered drought termination to be an instantaneous point in time. The exceptions to this are two studies which attempt to characterise a period of drought termination. Bonsal et al. (2011) sub-divided drought into six phases including drought termination (referred to as "recovery"), and Nkemdirim and Weber (1999) expressed the drought termination rate (referred to as "rate of recovery") using Palmer Drought Severity Index units over time.

Some preliminary steps have been taken to identify and characterise the spatial signature of a single drought termination for 15 catchments in the UK (Parry et al., 2016), and to apply the same assessment technique in a temporal analysis of drought terminations in a single catchment for the period 1883–2013 (Parry et al., 2015). By combining these spatial and temporal approaches, the aim of this study is to derive chronologies of drought termination metrics for 52 UK catchments. These data are then used to explore the link between drought termination metrics and catchment properties, and to assess the historical variability of drought termination. In due course, it is hoped that a better understanding of the physical processes driving drought termination will lead to improved water resources management and forecasting during these problematic episodes.

## 2 Data

Fifty-two catchments (Fig. 1; Table A1) were selected to maximise the spatio-temporal coverage of the dataset, both providing a representative coverage in the UK (accounting for more than 40 % of the gauged area) whilst capturing some of the longest river flow records. Nearly half (21 of 52) of the catchments are classified as near-natural, and these are predominantly located in northern and western areas of the UK. To the





HESSD
doi:10.5194/hess-2015-476

south and east and for the larger catchments, flows may be affected by anthropogenic influences, which have been shown to mask changes associated with drought termination (Ning et al., 2013). A naturalised river flow time series is used for the Thames; no other naturalised series are available for the study catchments. River flow data were obtained from the UK National River Flow Archive (NRFA). Start dates range between January 1883 and June 1982, but all series extend to September 2013. Time series of monthly mean river flow data were derived for each catchment for every month in which at least 90 % of the daily data were available. Metadata on catchment area, median elevation, Standard-period Average Annual Rainfall for 1961–1990 (hereafter SAAR6190; Spackman, 1993), Base Flow Index (hereafter BFI; Gustard et al., 1992), and urban extent (Marsh and Hannaford, 2008) were also obtained from the NRFA for each catchment (Table A1).

## 3 Methodology

Drought termination is defined here as a phase of a drought, rather than an instantaneous point in time. The threshold level method (Zelenhasić and Salvai, 1987) has been applied on a monthly time step, and drought events are sub-divided at the point of the maximum negative flow anomaly (Bravar and Kavvas, 1991) into two phases: drought development and drought termination (Fig. 2). Drought termination is characterised by its duration (e.g. Bonsal et al., 2011), rate of change (e.g. Correia et al., 1987; Nkemdirim and Weber, 1999), and seasonality (e.g. Mo, 2011).

For each catchment, monthly mean flow data were converted into a percentage anomaly of the monthly long-term average (LTA), calculated from a 1971–2000 reference period (Eq. 1).

$$Z_{\text{anom}_t} = 100\left(\left(Z_{\text{obs}_t}/Z_{\text{LTA}_m}\right) - 1\right), \tag{1}$$

where $t$ is the time step index, $m$ is the month of the time step, $Z_{\text{anom}_t}$ is the percentage anomaly at $t$, $Z_{\text{obs}_t}$ is the observed value at $t$, and $Z_{\text{LTA}_m}$ is the LTA at $m$.





HESSD
doi:10.5194/hess-2015-476

The start of a drought development phase ($t_{sd}$; Fig. 2) is the first month of $D$ consecutive months (pre-defined by the user) for which $Z_{anom_t}$ is negative. $R$ months within the $D$-month duration are permitted to be above average, to account for minor wet phases during drought development. Once a drought has been initiated, the end of the drought termination phase ($t_{et}$; Fig. 2) is the last month of $T$ consecutive months for which $Z_{anom_t}$ is greater than $Z_{LTA_m}$. The recovery threshold (RT; Fig. 2) is $Z_{anom_t}$ at $t_{et}$.

The end of the drought development phase ($t_{ed}$; Fig. 2) is the month with the largest negative $Z_{anom_t}$ value (defining the drought magnitude; DM, Fig. 2) between $t_{sd}$ and $t_{et}$. The start of the drought termination phase ($t_{st}$; Fig. 2) is the next month after $t_{ed}$.

The conceptual diagram in Fig. 2 illustrates the temporal stages of drought and some of the associated drought termination metrics. The drought termination duration (DTD; Fig. 2) is the number of months between $t_{st}$ and $t_{et}$. The drought termination rate (DTR; Fig. 2) is the difference between the drought magnitude and the recovery threshold, divided by the drought termination duration. The drought termination seasonality is a code relating to the seasons through which drought termination occurs. For example, if the start of drought termination is in autumn and the end of drought termination is in the next winter, the drought termination seasonality would be "Aut-Win".

In this study, the parameters are specified as $D = 10$, $R = 1$ and $T = 2$ (Fig. 2). The drought initiation parameters ($D$ and $R$) relate to persistent below average river flows for at least ten months to identify multi-season droughts, with an allowance for one month of above average flows. The drought cessation parameter ($T$; two consecutive months of above average river flows) has been chosen to avoid identifying intermittent high flows as the $t_{et}$. These values were applied to all of the study catchments.

To assess potential relationships with drought termination characteristics, Spearman correlations (Spearman, 1944) were calculated. This method was selected because testing has not been performed to assess whether the values of drought termination characteristics are normally distributed. Correlation analysis was performed on the whole dataset of 52 catchments, and on a smaller subset of catchments for which at least ten drought termination events were identified. This provided a more robust sam-





HESSD
doi:10.5194/hess-2015-476

ple size for deriving catchment average values of drought termination characteristics, which may smooth out inter-event variability and result in stronger correlations.

## 4 Results

### 4.1 Spatio-temporal variability of drought termination

Drought termination chronologies for all 52 catchments, approximately ordered from the north-west (top) to the south-east (bottom) of the UK, are presented in Fig. 3. This allows visual inspection of the spatial coherence of drought events over a common data period beginning in the early 1970s. Figure 3 shows that national-scale droughts have been relatively infrequent, occurring only in 1975–1977, 1995–1998, and possibly 2003–2004. Regional droughts affected southern and eastern areas in 1988–1993, 2004–2007 and 2009–2012. Drought-poor periods are also evident, the longest of which was the decade following the 1975–1977 event, during which there were few widespread or prolonged droughts.

Prior to 1970, a lack of river flow data before gauged records commenced (particularly in northern and western areas of the UK; Table A1) limits the assessment of the spatial coherence of drought phases, but events in 1962–1964, 1959 and 1943–1945 are identifiable. Persistent drought conditions (with intermittent drought terminations) within the 1890–1910 "Long Drought" are observed in the Thames river flow record from 1883.

Drought terminations show considerable spatio-temporal variability. For example, the 1988–1993 event had a notably uneven temporal evolution, with the transition to drought termination occurring early in the drought followed by a long drought termination phase for catchments in South-west UK, whereas shorter drought terminations were apparent in the rest of the country. Conversely, the drought termination in 1995–1998 was relatively coherent at a regional scale. Fewer droughts have occurred in northern and western areas of the UK than in southern and eastern areas, while





HESSD
doi:10.5194/hess-2015-476

drought terminations tend to occur over longer time periods in the south. However, it is important to note the wide range of variability in drought termination characteristics exhibited within individual catchments. Two events are singled out for more detailed analysis: 1995–1998, the most nationally coherent event in the post-1970 period; and 2009–2012, reported as unprecedented in the historical record (Parry et al., 2013).

### 4.2 Event analysis: 1995–1998

Drought in 1995–1998 affected all but one of the study catchments (Fig. 4; left), offering the best opportunity to analyse the spatial variability of drought termination within an individual episode. The overall duration of drought was generally longer (almost three years) further south and east in the UK. There were two distinct patterns of drought termination. In the north and west, the drought termination phase began within six months of the start of drought development and long drought termination phases (three or more seasons) followed in 13 catchments. In contrast, drought termination started almost two years later in 25 catchments, mainly in the south and east. The transition to drought termination was spatially coherent across North and Central Wales, Midlands, South-west UK and Southern England.

Drought termination durations were generally longer (by six to nine months) for catchments in Southern England, Thames and Anglian regions (Fig. 4; top right). Conventionally referred to as the 1995–1997 drought in the literature, it was the second half of 1998 before catchments in parts of lowland England (e.g. the Warwickshire Avon, Colne, Thames, Itchen and Dorset Avon) had completed the drought termination phase. The drought termination rate displayed a west–east divide in 1995–1998, particularly apparent for Wales and southern, central and eastern England (Fig. 4; middle right). Whilst much of Wales and south-west England exhibited drought termination rates of 16–32 % month$^{-1}$, this decreased to less than 8 % month$^{-1}$ across large areas of south-eastern England. Further north, the pattern was more mixed. Three-season drought terminations (Fig. 4; bottom right) started in the autumn in Scotland and in the





HESSD
doi:10.5194/hess-2015-476

winter in Wales and central and south-western England. Two-season drought terminations generally were confined to the far northern parts of Scotland and England.

### 4.3 Event analysis: 2009–2012

In contrast to the 1995–1998 event the 2009–2012 drought was regional, primarily affecting Wales and southern, central and eastern England. The temporal sequencing of drought termination was also more regionally variable than in 1995–1998. Drought terminations began much sooner (early summer 2010) in North-west England, and had ended whilst drought continued to develop further south (Fig. 5; left). Drought terminations started in South-west UK up to a year before those in central and eastern England. In the Midlands, Thames, Anglian and Southern England regions, drought termination began in winter 2011/2012 and ended in late spring or early summer 2012. The end of the drought termination phase was much more spatially coherent in 2009–2012 than in 1995–1998.

Drought termination durations in 2009–2012 were generally six months or less (Fig. 5; top right), much shorter than those for 1995–1998. There was a gradient in drought termination duration from north-east to south-west across the affected catchments. The shortest durations (1–3 months) occurred across southern, central and eastern England, but lasted longer (10–18 months) for catchments in South-west UK. The highest drought termination rates (more than 32 % month$^{-1}$) occurred in the largest catchments, whilst the lowest (less than 16 % month$^{-1}$) were restricted to smaller catchments in Northern Ireland, North-east England, South-west UK and Southern England (Fig. 5; middle right). Drought termination rate showed a similar gradient to drought termination duration. There was more uniformity in drought termination rate across the drought-affected area for 2009–2012 than in 1995–1998, and drought termination rates were generally more abrupt in 2009–2012.

There was a larger degree of seasonality for the 2009–2012 drought (Fig. 5; bottom right) than for the 1995–1998 event because drought terminations were generally shorter and started at different times. Catchments in southern, central and eastern





HESSD
doi:10.5194/hess-2015-476

England and north Wales experienced drought terminations through the summer half-year. Drought terminations through the winter months were not very common for the 2009–2012 event, restricted to the Warwickshire Avon (Midlands) and smaller catchments in the Anglian and Southern England regions.

### 4.4 Drought termination and catchment properties

The analysis above offers a qualitative assessment of the impact of catchment type on drought termination characteristics. Longer drought termination durations occurred in groundwater influenced catchments of southern and eastern England (e.g. the Stringside in Anglian and the Itchen and Dorset Avon in Southern England) in both 1995–1998 and 2009–2012. However, the synchronicity of the end of drought termination in spring 2012 (Fig. 5; left), when compared to the incoherent end of drought termination in 1995–1998 (Fig. 4; left), suggests that catchment properties are less influential during abrupt drought terminations than during gradual events.

Spearman correlations between drought termination characteristics (duration and rate) and five catchment properties (catchment area, median elevation, SAAR6190, BFI and urban extent) and two drought characteristics (drought magnitude and duration of drought development) were calculated from the complete catalogue of events. Correlations were assessed for individual events ($n = 459$) as well as for catchment averaged values ($n = 52$) (Table 1). Stronger correlations are found between catchment average drought termination characteristics and catchment properties than when drought termination events are considered individually. Correlations between characteristics of drought development and drought termination exhibit the opposite pattern. Three of these correlations weaken when using catchment averages, although one (drought magnitude and drought termination rate) strengthens. More of the correlations are statistically significant at the 95 % confidence level when using the individual event dataset ($n = 459$), particularly for correlations with drought termination rate, although correlations are weaker.





HESSD
doi:10.5194/hess-2015-476

The strongest correlation ($r_s = -0.48$; $p = 0.000407$) was found for catchment average drought termination duration and median elevation, suggesting that upland catchments tend to experience shorter drought terminations. Although slightly weaker, correlations with SAAR6190 ($r_s = -0.40$; $p = 0.00366$) show a similar pattern, possibly explained by notable autocorrelation between elevation and rainfall ($r_s = 0.71$; $p = 2.03 \times 10^{-8}$). Drought termination rate and urban extent are negatively correlated ($r_s = -0.43$; $p = 0.00172$). Correlations between the BFI and drought termination rate are relatively weak.

Spearman correlations were also derived for a subset of the study catchments (not shown), with 17 out of the 52 meeting the criteria of at least ten identified drought termination events. A stronger (though not statistically significant) link was found between catchment average drought termination rate and BFI ($r_s = -0.36$; $p = 0.156$). This implies that lower BFI (i.e. more responsive) catchments tend to have faster drought termination rates (i.e. more abrupt). For this subset of catchments, relationships between drought termination duration and both elevation and rainfall remained the strongest, but the linkages between urban extent and both drought termination duration and drought termination rate were comparable.

For correlations between drought termination characteristics and those of the preceding drought development phase, although relatively weak the strongest relationships were detected for drought development duration with both drought termination duration ($r_s = -0.30$; $p = 1.07 \times 10^{-10}$) and drought termination rate ($r_s = 0.28$; $p = 7.35 \times 10^{-10}$). This suggests that prolonged drought development phases tend to be followed by shorter and more abrupt drought terminations. Relationships with catchment average drought development characteristics are not statistically significant, but assessments with the larger individual event dataset found that most linkages (e.g. drought magnitude and drought termination duration, drought development duration and drought termination rate) are significant at the 95 % level.





HESSD
doi:10.5194/hess-2015-476

## 5 Discussion

This study has systematically defined drought terminations in the historical river flow record for the UK for the first time. The approach has identified 459 drought events across 52 study catchments, providing a comprehensive dataset for further analysis of the historical variability of drought termination. Two aspects were explored: a preliminary assessment of linkages between drought termination characteristics and catchment properties, including features of the preceding drought development phase (informed by the correlation analysis above); and a re-appraisal of drought termination characteristics in 2009–2012 within a hydrological context.

### 5.1 Drought termination characteristics and catchment properties

The spatio-temporal variability in drought termination within individual events (Figs. 3–5) is partly related to catchment properties that modulate the rainfall inputs. This reflects other studies that found hydrological drought termination to be more spatially variable than drought development, owing to the heterogeneity of catchment characteristics (e.g. Nkemdirim and Weber, 1999; Bell et al., 2013; DeChant and Moradkhani, 2015).

Some of the strongest correlations were found between drought termination duration and both elevation and catchment average rainfall (SAAR6190). This is likely to be because catchments in wetter upland areas of the UK are typically impermeable and responsive to rainfall, translating to shorter drought terminations. The correlations between urban extent and both drought termination duration and drought termination rate imply that drought terminations tend to be longer and more gradual in catchments with larger urban areas. This contradicts the expectation that typically impermeable urban areas may exhibit more abrupt drought terminations. The more urbanised catchments of the UK are generally in the south-east with more permeable geology and it may be that lower responsiveness to rainfall negates the impact of the urban extent. Note also that the urban extent data are based on satellite imagery from 1998–2000 and there-



HESSD
doi:10.5194/hess-2015-476

A systematic assessment of drought termination in the United Kingdom

S. Parry et al.

fore do not reflect the changing proportion of a catchment as built area through the 20th century. Further analysis will be required to assess the impact of increasing urbanisation on trends in drought termination characteristics within the study catchments.

The BFI is widely regarded as a proxy for groundwater influence in the UK. However, water storage in lakes and seasonal snowpacks can also be locally important, with BFI values of 0.43–0.60 for the Spey, Deveron, Scottish Dee and Naver in northern Scotland despite negligible groundwater influence. Whilst these impermeable catchments typically respond rapidly to rainfall, catchments with similar BFI values in areas of groundwater influence further south are less responsive. Elevation is a better indicator of the spatial variability of geology in the UK than BFI, which may explain why correlations between drought termination characteristics and elevation are stronger than those with BFI. By excluding catchments in Scotland that exhibit mismatches between BFI and responsiveness (through the use of the subset of 17 catchments with at least ten events), the correlation analysis found a stronger association between drought termination rate and BFI. This linkage, as well as the qualitative observation of longer drought terminations in groundwater influenced catchments, is consistent with previous studies that report longer duration drought termination in subsurface storage (Thomas et al., 2014) and groundwater levels (e.g. Eltahir and Yeh, 1999).

The stronger relationships identified in the larger dataset between drought development and drought termination characteristics suggest that catchment averaging both metrics before correlation may smooth out unique pairs of characteristics, resulting in information loss and obscuring any detectable signal. Weak negative (although statistically significant) correlation was found between drought magnitude and drought termination duration, contrary to a pattern observed for two multi-year droughts in the US (Nkemdirim and Weber, 1999). The most important linkages identified between drought development and drought termination characteristics were for drought development duration with both drought termination duration and drought termination rate. This suggests that there may be critical thresholds of drought development duration, beyond which complete drought termination is unlikely except in the most extreme scenarios (short duration and/or high rate of drought termination). Although these correlations are only moderate and require further analysis, there may be important implications for the management of water resources beyond any possible critical time threshold within a drought.

## 5.2 Drought termination rate for 2009–2012 in a historical context

The rate of drought termination in 2009–2012 was particularly abrupt, more so than any other event identified in the post-1970 common data period. Almost a third (nine out of 31) of the drought-affected catchments in 2009–2012 registered new maxima for drought termination rate (Table 2). For the Severn, the drought termination in 2009–2012 was almost four times more abrupt than any other event since 1929, and ranked amongst the top five most abrupt drought terminations for *any* event in *any* of the 52 study catchments ($n = 459$). Drought magnitudes were not exceptional but it was the differences between drought magnitudes and recovery thresholds over such short drought termination durations in 2009–2012 that were particularly influential in establishing new maximum drought termination rates. This suggests that exceptional rainfall over short durations (assessed as greater than a 100-year return period; Bell et al., 2013) was a more important factor than the severity of the preceding drought.

Research conducted in the immediate aftermath of the 2009–2012 event suggested that the drought termination was unprecedented in the historical record (Parry et al., 2013; Marsh et al., 2013). However, the assessment of the rarity of such abrupt transitions was based on ratios between average flows over arbitrarily defined periods (May–July and the preceding December–March; Fig. 6). The systematic approach adopted here allows an objective re-appraisal of the historical context across all timeframes. Although the drought termination event in 2009–2012 remains the most abrupt on record for the Thames (Table 2), there were three other comparably abrupt drought terminations between 1883 and 1930. This suggests that the rarity of the 2009–2012 drought termination may have been overstated in previous work (in the specific case of the Thames).





HESSD
doi:10.5194/hess-2015-476

Although difficult to assess consistently prior to 1970 due to limitations in data availability, the termination phases in 2009–2012 and 2004–2007 were the most abrupt on record for nine and eight of the 52 catchments, respectively; no other event registered record maxima in more than five catchments. These severe multi-year droughts featured consecutive dry winters (Wilby et al., 2016), perhaps suggesting that long droughts result in more abrupt drought termination phases. They are also the most recent of the identified events, although the suggestion that drought termination rates have become more abrupt in the recent past requires further exploration. The characteristics of the 2009–2012 drought termination are consistent with studies that describe drought termination as abrupt (e.g. Dettinger, 2013), and more rapid than drought development (e.g. Mo, 2011). However, the wide range of drought termination rates both between and within catchments suggests that different drought termination mechanisms are plausible. Drought termination is a complex interplay of the specific hydroclimatic conditions and catchment properties, even for groundwater influenced permeable catchments (in which the rainfall signal is substantially modulated). Groundwater drought termination has been observed to be much slower than drought development in the western US (Bravar and Kavvas, 1991). Whether this applies to individual events in groundwater influenced catchments in this study would depend on the extent to which deficits have propagated to groundwater. The depletion of groundwater aquifers in Southern England may also have impacted drought termination characteristics in some catchments (e.g. the Itchen). The approach adopted in this study could be applied to groundwater level records where they exist within the catchments, although this is beyond the scope of this analysis. Similar variability in drought terminations was also found by Bonsal et al. (2011), and was attributed by Kam et al. (2013) to differences in rainfall intensity determined by the type of synoptic drivers (e.g. tropical cyclones).

### 5.3 Drought termination seasonality for 2009–2012 in a historical context

The drought termination in 2009–2012 occurred through the spring and early summer, an unusual but not unprecedented occurrence. Only nine of the 459 drought termina-





HESSD
doi:10.5194/hess-2015-476

A systematic assessment of drought termination in the United Kingdom

S. Parry et al.

tions occurred entirely in spring or in summer. Five of these nine relate to the 2009–2012 event (the Severn, Trent, Derwent and Witham in spring, and the Colne in summer). With the exception of the Severn, the drought termination in 2009–2012 is the only single season event in the historical record for each catchment. Drought terminations across both spring and summer are similarly uncommon. Of the 13 events (out of 459) with spring-summer drought termination seasonality, five occurred in 2009–2012 (the Yscir, Exe, Thames, Itchen and Sydling Water). Of the remaining eight events, no other drought termination is represented by more than two catchments. For the Thames, the only previous example of a drought termination entirely within the spring and summer was in 1888. Other studies have also found that it is difficult to terminate multi-season droughts in two seasons or less (Karl et al., 1987).

Rather than simply the wettest season, it is the season with the greatest potential for large positive rainfall anomalies that are most likely to facilitate drought termination (Karl et al., 1987; Mo, 2011). In the UK, these two factors are coincident, so the winter provides the greatest likelihood for drought termination (Van Loon et al., 2014). The larger evaporative demand in summer reduces the effectiveness of all but the most extreme rainfall, explaining the skewed distribution of drought terminations towards the winter half-year. Of the 459 drought terminations, single season events were more common in autumn (eight) and winter (eight) than in spring (six) and particularly summer (three).

At regional scales, variation in drought termination seasonality is likely to be determined by catchment properties, such as storage causing lagged responses. For catchments in Scotland, the influence of snow may also influence drought termination. Where seasonal snowpacks exist, winter drought terminations may be delayed until the snowmelt season (Van Loon et al., 2014). However, the large variability of drought termination characteristics and the moderate to weak correlations with catchment properties imply that a range of physical processes exist. At national or continental scales, variability in drought termination seasonality is likely to be influenced by larger scale drivers such as El Niño and La Niña events in the Pacific (e.g. Tomasella et al., 2011;

Marengo and Espinoza, 2015), switches in Atlantic temperatures (Wilby, 2001; Folland et al., 2015), or tropical cyclones (e.g. Patterson et al., 2013).

## 6 Conclusions

For the first time, drought terminations have been systematically identified in the UK. This analysis detected 459 events in 52 catchments covering a range of geographical settings, and provides chronologies of both drought development and drought termination phases. This information gives a new perspective to the historical variability of drought termination in the UK that is potentially useful for water resource managers and researchers in a range of fields including ecology, geomorphology and water quality. It is hoped that characterising 459 drought termination events will underpin trend analyses and provide the basis for the development of a drought termination typology.

Although the identification procedure applied consistent rules, the parameter values set to define a drought and its phases influence the chronologies. The parameters were chosen to maximise the detection of multi-season events. Drought termination phases following shorter drought developments driven by summer heatwaves, for example, would not be well represented by the parameter settings used in this study. In addition, events in the more hydrologically responsive north and west of the UK might be less well represented because droughts in these wetter regions are typically shorter than multi-season in duration. However, the spatial variability in the number of identified droughts is consistent with the levels of service offered by regional water companies, with drought-induced water restrictions expected more frequently in the south-east of the UK than in the north.

The use of a monthly time step in this study may also restrict the approach. Drought termination can occur rapidly, within a few days, particularly in hydroclimatic settings in which the end of a drought is often triggered by tropical cyclone activity. In such locations, the application of the approach used in this study may obscure accurate





HESSD
doi:10.5194/hess-2015-476

definitions of the end of drought termination or underestimate the drought termination rate.

The potential influence of abstractions from surface and groundwater sources during drought development may artificially increase the duration of the drought termination phase. The study catchments include some of the largest in the UK in order to maximise spatial coverage, and few of these could be described as near-natural. Abstractions to meet higher demand during drought development, particularly during heatwave conditions, are superimposed upon restricted recharge. Drought-terminating rainfall must account for this "anthropogenic deficit" in addition to the natural river flow deficiencies.

Investigations into the link between drought termination characteristics and catchment properties or drought development characteristics would benefit from a larger sample of events. This is illustrated by the stronger correlations found for catchment average drought termination metrics when using the subset of catchments with at least ten identified events, although this subset is biased towards catchments with longer records predominantly in southern and eastern areas of the UK. The BFI is not an adequate metric of the responsiveness of a catchment. Further exploration of potential linkages between drought termination characteristics and catchment properties should seek to use variables which are more closely related to river flow responsiveness than BFI. Potential associations between drought termination characteristics and those of the preceding drought development phase may be useful for water resource managers in plotting near real-time drought termination trajectories based on the evolution of drought.

The identification and characterisation of 459 drought terminations has provided a comprehensive historical context within which to place the 2009–2012 event. This illustrates the variability of drought termination characteristics in the UK, re-assessing the conclusion (based on a subset of newsworthy examples) that droughts tend to terminate abruptly. The long-term context could be improved further through the use of river flow reconstructions (e.g. Jones and Lister, 1998; Jones et al., 2006) to "fill in the grey





HESSD
doi:10.5194/hess-2015-476

space” in Fig. 3, which represents the best historical perspective provided by available observed data. Similarly comprehensive chronologies of drought termination in groundwater level records and other hydrometeorological variables have not yet been produced. The method used in this study has the flexibility to be applied to these and other metrics (e.g. water quality and ecological indices), to trace the propagation of drought termination throughout the river system.

*Author contributions.* S. Parry devised the approach and selected the catchments. R. L. Wilby provided input on the structure and content of the paper and the impetus for the correlation analysis. C. Prudhomme provided feedback on the different paper structures and contents proposed. S. Parry wrote the manuscript with constructive comments from R. L. Wilby, C. Prudhomme and P. J. Wood.

*Acknowledgements.* This research was funded through the Learning and Development programme at the Centre for Ecology and Hydrology (CEH), as well as the Natural Environment Research Council’s (NERC) “Analysis of historic drought and water scarcity in the UK” (NERC Grant Ref.: NE/L01016X/1) and “IMPETUS” (NERC Grant Ref.: NE/L010267/1) projects. River flow data and catchment metadata were provided by the UK National River Flow Archive at CEH. The authors would also like to thank Katie Muchan, Filip Kral and Lucy Barker (all CEH) for their assistance with river flow data and metadata, spatial data, and graphics, respectively.

## References

Bell, V. A., Davies, H. N., Kay, A. L., Marsh, T. J., Brookshaw, A., and Jenkins, A.: Developing a large-scale water-balance approach to seasonal forecasting: application to the 2012 drought in Britain, Hydrol. Process., 27, 3003–3012, 2013.

Bonsal, B. R., Wheaton, E. E., Meinert, A., and Siemens, E.: Characterizing the surface features of the 1999–2005 Canadian prairie drought in relation to previous severe twentieth century events, Atmos. Ocean, 49, 320–338, 2011.

Bravar, L. and Kavvas, M. L.: On the physics of droughts. II. Analysis and simulation of the interaction of atmospheric and hydrologic processes during droughts, J. Hydrol., 129, 299–330, 1991.

Chew, C. C. and Small, E. E.: Terrestrial water storage response to the 2012 drought estimated from GPS vertical position anomalies, Geophys. Res. Lett., 41, 6145–6151, 2014.
Correia, F. N., Santos, M. A., and Rodrigues, R. R.: Engineering risk in regional drought studies, in: Engineering Reliability and Risk in Water Resources, edited by: Duckstein, L. and Plate, E. J., Proceedings of the NATO Advanced Study Institute on "Engineering Reliability and Risk in Water Resources", Tuscon, Arizona, USA, 19 May–2 June 1985, Martinus Nijhoff Publishers, Dordrecht, 1987.
DeChant, C. M. and Moradkhani, H.: Analyzing the sensitivity of drought recovery forecasts to land surface initial conditions, J. Hydrol., 526, 89–100, 2015.
Dettinger, M. D.: Atmospheric rivers as drought busters on the US West Coast, J. Hydrometeorol., 14, 1721–1732, 2013.
Doornkamp, J. C., Gregory, K. J., and Burn, A. S.: Atlas of Drought in Great Britain, Institute of British Geographers, London, 1980.
Eltahir, E. A. B. and Yeh, P. J.-F.: On the asymmetric response of aquifer water level to floods and droughts in Illinois, Water Resour. Res., 35, 1199–1217, 1999.
Fleig, A. K., Tallaksen, L. M., Hisdal, H., and Hannah, D. M.: Regional hydrological drought in north-western Europe: linking a new Regional Drought Area Index with weather types, Hydrol. Process., 25, 1163–1179, 2011.
Folland, C. K., Hannaford, J., Bloomfield, J. P., Kendon, M., Svensson, C., Marchant, B. P., Prior, J., and Wallace, E.: Multi-annual droughts in the English Lowlands: a review of their characteristics and climate drivers in the winter half-year, Hydrol. Earth Syst. Sci., 19, 2353–2375, doi:10.5194/hess-19-2353-2015, 2015.
Gustard, A., Bullock, A., and Dixon, J. M.: Low Flow Estimation in the United Kingdom, Institute of Hydrology Report No. 108, 1992.
Hisdal, H., Stahl, K., Tallaksen, L. M., and Demuth, S.: Have streamflow droughts in Europe become more severe or frequent?, Int. J. Climatol., 21, 317–333, 2001.
Jones, P. D. and Lister, D. H.: Riverflow reconstructions for 15 catchments over England and Wales and an assessment of hydrologic drought since 1865, Int. J. Climatol., 18, 999–1013, 1998.
Jones, P. D., Lister, D. H., Wilby, R. L., and Kostopoulou, E.: Extended riverflow reconstructions for England and Wales, 1865–2002, Int. J. Climatol., 26, 219–231, 2006.
Kam, J., Sheffield, J., Yuan, X., and Wood, E. F.: The influence of Atlantic tropical cyclones on drought over the Eastern United States, J. Climate, 26, 3067–3086, 2013.





HESSD
doi:10.5194/hess-2015-476

Karl, T., Quinlan, F., and Ezell, D. S.: Drought termination and amelioration: its climatological probability, J. Clim. Appl. Meteorol., 26, 1198–1209, 1987.
Kienzle, S. W.: The use of the recession index as an indicator for streamflow recovery after a multi-year drought, Water Resour. Manag., 20, 991–1006, 2006.
Lam, H., Kok, M. H., and Shum, K. K. Y.: Benefits from typhoons – the Hong Kong perspective, Weather, 67, 16–20, 2012.
Lange, J. and Haensler, A.: Runoff generation following a prolonged dry period, J. Hydrol., 464–465, 157–164, 2012.
Lavers, D. A. and Villarini, G.: Were global numerical weather prediction systems capable of forecasting the extreme Colorado rainfall of 9–16 September 2013?, Geophys. Res. Lett., 40, 1–6, 2013.
Leblanc, M. J., Tregoning, P., Ramillien, G., Tweed, S. O., and Fakes, A.: Basin-scale, integrated observations of the early 21st century multiyear drought in southeast Australia, Water Resour. Res., 45, W04408, doi:10.1029/2008WR007333, 2009.
Li, S., Xiong, L., Dong, L., and Zhang, J.: Effects of the Three Gorges Reservoir on the hydrological droughts at the downstream Yichang station during 2003–2011, Hydrol. Process., 27, 3981–3993, 2013.
Marengo, J. A. and Espinoza, J. C.: Extreme seasonal droughts and floods in Amazonia: causes, trends and impacts, Int. J. Climatol., doi:10.1002/joc.4420, 2015.
Marengo, J. A., Nobre, C. A., Tomasella, J., Oyama, M. D., de Oliveira, G. S., de Oliveira, R., Camargo, H., Alves, L. M., and Brown, I. F.: The Drought of Amazonia in 2005, J. Climate, 21, 495–516, 2008.
Marsh, T. J. and Hannaford, J. (Eds.): UK Hydrometric Register, Hydrological Data UK Series, NERC Centre for Ecology and Hydrology, Wallingford, 2008.
Marsh, T., Cole, G., and Wilby, R.: Major droughts in England and Wales, 1800–2006, Weather, 62, 87–93, 2007.
Marsh, T. J., Parry, S., Kendon, M. C., and Hannaford, J.: The 2010–12 Drought and Subsequent Extensive Flooding, NERC Centre for Ecology and Hydrology, Wallingford, 2013.
Maxwell, J. T., Ortegen, J. T., Knapp, P. A., and Soule, P. T.: Tropical cyclones and drought amelioration in the Gulf and Southeastern Coastal United States, J. Climate, 26, 8440–8452, 2013.
Miller, J. D., Gaskin, G. J., and Anderson, H. A.: From drought to flood: catchment responses revealed using novel soil water probes, Hydrol. Process., 11, 533–541, 1997.





HESSD
doi:10.5194/hess-2015-476

A systematic assessment of drought termination in the United Kingdom

S. Parry et al.

Mo, K. C.: Drought onset and recovery over the United States, J. Geophys. Res., 116, D20106, doi:10.1029/2011JD016168, 2011.
Ning, N. S. P., Gawne, B., Cook, R. A., and Nielsen, D. L.: Zooplankton dynamics in response to the transition from drought to flooding in four Murray–Darling basin rivers affected by differing levels of flow regulation, Hydrobiologia, 702, 45–62, 2013.
Nkemdirim, L. and Weber, L.: Comparison between the droughts of the 1930s and the 1980s in the Southern Prairies of Canada, J. Climate, 12, 2434–2450, 1999.
Parry, S., Marsh, T., and Kendon, M.: 2012: from drought to floods in England and Wales, Weather, 68, 268–274, 2013.
Parry, S., Prudhomme, C., Wilby, R. L., and Wood, P. J.: Chronology of drought termination for long records in the Thames catchment, in: Drought: Research and Science-Policy Interfacing, edited by: Andreu, J., Solera, A., Paredes-Arquiola, J., Haro-Monteagudo, D., and Van Lanen, H. A. J., CRC Press/Balkema, Leiden, 165–170, 2015.
Parry, S., Prudhomme, C., Wilby, R. L., and Wood, P. J.: Drought termination: concept and characterisation, submitted to: Prog. Phys. Geog., in review, 2016.
Patterson, L. A., Lutz, B. D., and Doyle, M. W.: Characterization of drought in the South Atlantic, United States, J. Am. Water Resour. As., 49, 1385–1397, 2013.
Pfister, C., Weingartner, R., and Luterbacher, J.: Hydrological winter droughts over the last 450 years in the Upper Rhine basin: a methodological approach, Hydrolog. Sci. J., 51, 966–985, 2006.
Shukla, S., Steinemann, A. C., and Lettenmaier, D. P.: Drought monitoring for Washington State: indicators and applications, J. Hydrometeorol., 12, 66–83, 2011.
Spackman, E.: Calculation and Mapping of Rainfall Averages for 1961–90, University of Salford, Manchester, 1993.
Spearman, C. E.: “General intelligence”, objectively determined and measured, Am. J. Psychol., 15, 201–293, 1944.
Thomas, A. C., Reager, J. T., Famiglietti, J. S., and Rodell, M.: A GRACE-based water storage deficit approach for hydrological drought characterization, Geophys. Res. Lett., 41, 1537–1545, 2014.
Tomasella, J., Borma, L. S., Marengo, J. A., Rodriguez, D. A., Cuartas, L. A., Nobre, C. A., and Prado, M. C. R.: The droughts of 1996–1997 and 2004–2005 in Amazonia: hydrological response in the river main-stem, Hydrol. Process., 25, 1228–1242, 2011.





HESSD
doi:10.5194/hess-2015-476

A systematic assessment of drought termination in the United Kingdom

S. Parry et al.

Van Loon, A. F., Tijdeman, E., Wanders, N., Van Lanen, H. A. J., Teuling, A. J., and Uijlenhoet, R.: How climate seasonality modifies drought duration and deficit, J. Geophys. Res., 119, 4640–4656, 2014.
Wang, H., Jia, L., Steffen, H., Wu, P., Jiang, L., Hsu, H., Xiang, L., Wang, Z., and Hu, B.: Increased water storage in North America and Scandinavia from GRACE gravity data, Nat. Geosci., 6, 38–42, 2013.
Webster, P. J., Toma, V. E., and Kim, H.-M.: Were the 2010 Pakistan floods predictable?, Geophys. Res. Lett., 38, L04806, doi:10.1029/2010GL046346, 2011.
Wilby, R. L.: Downscaling summer rainfall in the UK from North Atlantic ocean temperatures, Hydrol. Earth Syst. Sci., 5, 245–257, doi:10.5194/hess-5-245-2001, 2001.
Wilby, R. L., Prudhomme, C., Parry, S., and Muchan, K. G. L.: Persistence of hydrometeorological droughts in the United Kingdom: a regional analysis of multi-season rainfall and river flow anomalies, J. Extreme Events (special issue), doi:10.1142/S2345737615500062, in press, 2016.
Yang, S., Wu, B., Zhang, R., and Zhou, S.: Relationship between an abrupt drought-flood transition over mid-low reaches of the Yangtze River in 2011 and the intra-seasonal oscillation over mid-high latitudes, Acta Meteorol. Sinica, 27, 129–143, 2012.
Zelenhasić, E. and Salvai, A.: A method of streamflow drought analysis, Water Resour. Res., 23, 156–168, 1987.





HESSD
doi:10.5194/hess-2015-476

A systematic assessment of drought termination in the United Kingdom

S. Parry et al.

**Table 1.** Spearman correlations for relationships between drought termination characteristics and both catchment properties and drought development characteristics. Correlations are presented for individual events (rows for which $n = 459$) and for catchment mean drought characteristics (rows for which $n = 52$). Values indicated with an asterisk (*) are statistically significant at the 95 % confidence level. Drought termination characteristics denoted as follows: DTD = drought termination duration; DTR = drought termination rate. Drought development characteristics are denoted as follows: DDD = drought development duration; DM = drought magnitude. Catchment properties are denoted as follows: SAAR6190 = Standard-period Average Annual Rainfall for 1961–1990; BFI = Base Flow Index.

| | | Catchment properties | | | | | Drought development characteristics | |
|---|---|---|---|---|---|---|---|---|
| | *n* | Area | Median elevation | SAAR6190 | BFI | Urban extent | DDD | DM |
| DTD | 459 | −0.03 | −0.15* | −0.12* | 0.04 | 0.14* | −0.30* | −0.19* |
| DTD | 52 | −0.23 | −0.48* | −0.40* | 0.13 | 0.40* | 0.03 | −0.06 |
| DTR | 459 | 0.02 | 0.12* | 0.12* | −0.18* | −0.15* | 0.28* | −0.04 |
| DTR | 52 | 0.11 | 0.22 | 0.12 | −0.12 | −0.43* | 0.01 | −0.19 |



HESSD
doi:10.5194/hess-2015-476

A systematic assessment of drought termination in the United Kingdom

S. Parry et al.

**Table 2.** Study catchments which established new period of record maximum drought termination rates in 2009–2012.

| Catchment | Drought termination rate (% month$^{-1}$) | Rank (out of total number) | Drought termination rate (% month$^{-1}$) for rank 2 | Year of drought termination ranking 2nd by drought termination rate |
|---|---|---|---|---|
| Severn | 90.6 | 1/16 | 26.5 | 1997 |
| Derwent | 62.3 | 1/7 | 42.6 | 1976 |
| Trent | 56.3 | 1/11 | 28.0 | 1959/1960 |
| Warwickshire Avon | 49.6 | 1/20 | 33.7 | 1963 |
| Thames | 38.1 | 1/35 | 37.2 | 1929/1930 |
| Teme | 33.6 | 1/8 | 29.6 | 1975/1976 |
| Sydling Water | 30.8 | 1/10 | 25.5 | 1974 |
| Itchen | 21.1 | 1/9 | 12.5 | 1963 |
| Carron | 18.2 | 1/3 | 11.9 | 2001 |





HESSD
doi:10.5194/hess-2015-476

**Table A1.** Gauging station metadata for the 52 study catchments.

| Region | Catchment | Record length (years) | Area ($km^2$) | Median elevation (m) | SAAR6190 (mm) | BFI | Urban extent (%) |
|---|---|---|---|---|---|---|---|
| W Scotland | Naver | 37 | 477 | 187 | 1384 | 0.43 | 0.0 |
| W Scotland | Carron | 35 | 138 | 342 | 2620 | 0.26 | 0.0 |
| W Scotland | Nevis | 32 | 69 | 518 | 2912 | 0.27 | 0.1 |
| W Scotland | Clyde | 51 | 1903 | 252 | 1129 | 0.46 | 3.0 |
| W Scotland | Ayr | 38 | 574 | 212 | 1214 | 0.30 | 0.6 |
| W Scotland | Cree | 51 | 368 | 212 | 1760 | 0.28 | 0.2 |
| W Scotland | Nith | 37 | 477 | 288 | 1460 | 0.39 | 0.2 |
| E Scotland | Findhorn | 56 | 782 | 408 | 1064 | 0.40 | 0.0 |
| E Scotland | Spey | 62 | 2861 | 420 | 1120 | 0.60 | 0.1 |
| E Scotland | Deveron | 54 | 955 | 209 | 928 | 0.57 | 0.2 |
| E Scotland | Scottish Dee | 85 | 1370 | 508 | 1109 | 0.53 | 0.1 |
| E Scotland | Tay | 62 | 4587 | 395 | 1425 | 0.65 | 0.2 |
| E Scotland | Forth | 33 | 1036 | 180 | 1752 | 0.41 | 0.0 |
| E Scotland | Whiteadder Water | 45 | 503 | 230 | 813 | 0.51 | 0.2 |
| E Scotland | Tweed | 52 | 4390 | 255 | 955 | 0.52 | 0.3 |
| N Ireland | Mourne | 32 | 1844 | 153 | 1288 | 0.39 | 0.3 |
| N Ireland | Faughan | 38 | 273 | 173 | 1219 | 0.47 | 0.4 |
| N Ireland | Lagan | 42 | 492 | 95 | 916 | 0.43 | 3.2 |
| NW England | Eden | 47 | 2287 | 210 | 1183 | 0.49 | 0.8 |
| NW England | Kent | 46 | 209 | 205 | 1732 | 0.41 | 1.8 |
| NW England | Ribble | 54 | 1145 | 198 | 1353 | 0.34 | 3.7 |
| NE England | South Tyne | 52 | 751 | 333 | 1148 | 0.34 | 0.2 |
| NE England | Tees | 58 | 818 | 370 | 1141 | 0.34 | 0.4 |
| NE England | Ure | 56 | 915 | 264 | 1118 | 0.39 | 0.8 |
| NE England | Derwent | 41 | 1586 | 102 | 765 | 0.70 | 0.8 |
| N&C Wales | Conwy | 50 | 345 | 328 | 2055 | 0.28 | 0.1 |
| N&C Wales | Welsh Dee | 77 | 1013 | 347 | 1369 | 0.54 | 0.4 |
| N&C Wales | Severn | 93 | 4325 | 127 | 913 | 0.53 | 2.0 |
| N&C Wales | Teme | 44 | 1480 | 191 | 818 | 0.55 | 0.7 |
| N&C Wales | Wye | 78 | 4010 | 199 | 1011 | 0.54 | 0.7 |





HESSD
doi:10.5194/hess-2015-476

**Table A1.** Continued.

| Region | Catchment | Record length (years) | Area ($km^2$) | Median elevation (m) | SAAR6190 (mm) | BFI | Urban extent (%) |
|---|---|---|---|---|---|---|---|
| Midlands | Trent | 56 | 7486 | 118 | 761 | 0.64 | 10.5 |
| Midlands | Warwickshire Avon | 78 | 2210 | 96 | 654 | 0.51 | 4.9 |
| SW UK | Tywi | 56 | 1090 | 220 | 1534 | 0.47 | 0.2 |
| SW UK | Yscir | 42 | 63 | 361 | 1299 | 0.46 | 0.0 |
| SW UK | Tone | 53 | 202 | 120 | 966 | 0.60 | 1.6 |
| SW UK | Torridge | 54 | 663 | 146 | 1186 | 0.38 | 0.4 |
| SW UK | Exe | 58 | 601 | 235 | 1248 | 0.50 | 0.6 |
| SW UK | Dart | 56 | 248 | 347 | 1765 | 0.52 | 0.7 |
| SW UK | Warleggan | 45 | 25 | 232 | 1442 | 0.70 | 0.2 |
| SW UK | Sydling Water | 45 | 12 | 190 | 1032 | 0.88 | 0.5 |
| Anglian | Lud | 46 | 55 | 89 | 699 | 0.90 | 2.2 |
| Anglian | Witham | 55 | 298 | 91 | 614 | 0.69 | 3.5 |
| Anglian | Bedford Ouse | 81 | 1460 | 101 | 636 | 0.53 | 3.5 |
| Anglian | Stringside | 49 | 99 | 20 | 629 | 0.84 | 0.7 |
| Anglian | Wensum | 45 | 398 | 57 | 684 | 0.75 | 1.3 |
| Anglian | Colne | 55 | 238 | 68 | 566 | 0.52 | 2.2 |
| S England | Thames | 131 | 9948 | 100 | 706 | 0.63 | 6.6 |
| S England | Great Stour | 50 | 345 | 75 | 747 | 0.70 | 3.2 |
| S England | Bull | 36 | 41 | 58 | 820 | 0.37 | 0.9 |
| S England | Itchen | 56 | 360 | 107 | 833 | 0.96 | 2.9 |
| S England | Dorset Avon | 49 | 324 | 129 | 745 | 0.91 | 1.3 |
| S England | Stour | 41 | 1073 | 83 | 861 | 0.64 | 2.0 |





HESSD
doi:10.5194/hess-2015-476

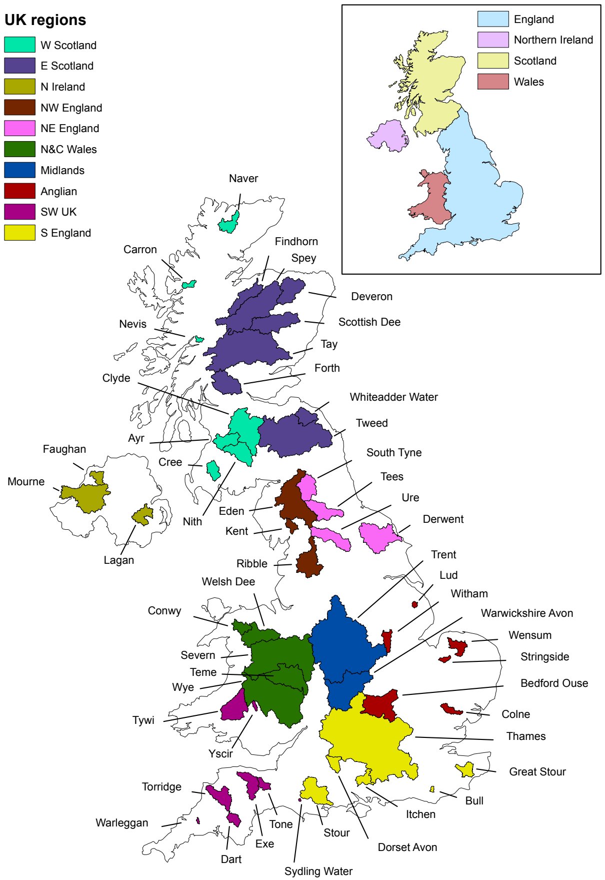


**Figure 1.** Location of the 52 study catchments in the UK, colour-coded by their region. Inset: the constituent countries of the UK.





HESSD
doi:10.5194/hess-2015-476

A systematic assessment of drought termination in the United Kingdom

S. Parry et al.

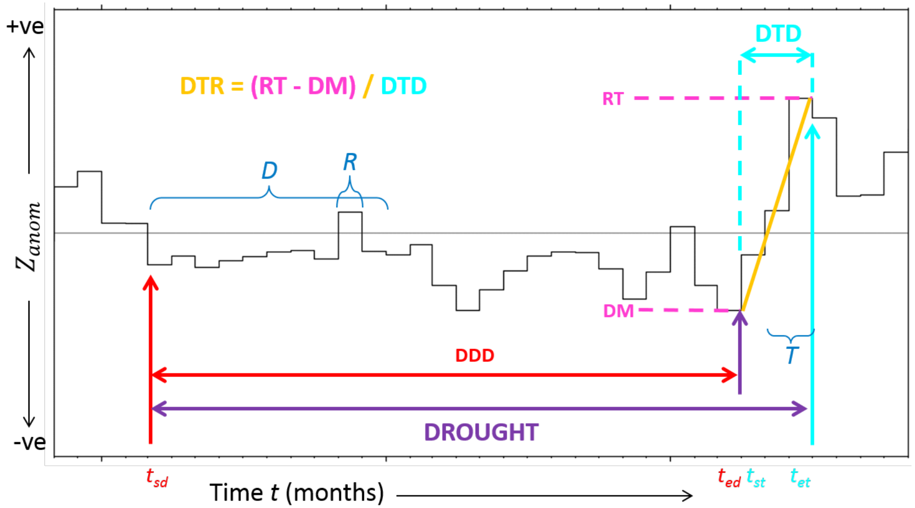


**Figure 2.** Conceptual diagram of drought termination definition and metrics. The three parameters are as follows: $D$ is the number of months of below average flows required for the drought development phase to begin; $R$ is the number of months of intermittent above average flows permitted within $D$; and $T$ is the number of months of above average flows required for the end of the drought termination phase. $t_{\text{sd}}$ is the start of drought development, $t_{\text{ed}}$ is the end of drought development, $t_{\text{st}}$ is the start of drought termination, and $t_{\text{et}}$ is the end of drought termination. The grey horizontal line represents an anomaly of zero, below which flows are below average and above which flows are above average.





HESSD
doi:10.5194/hess-2015-476



Title Page
Abstract Introduction
Conclusions References
Tables Figures
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

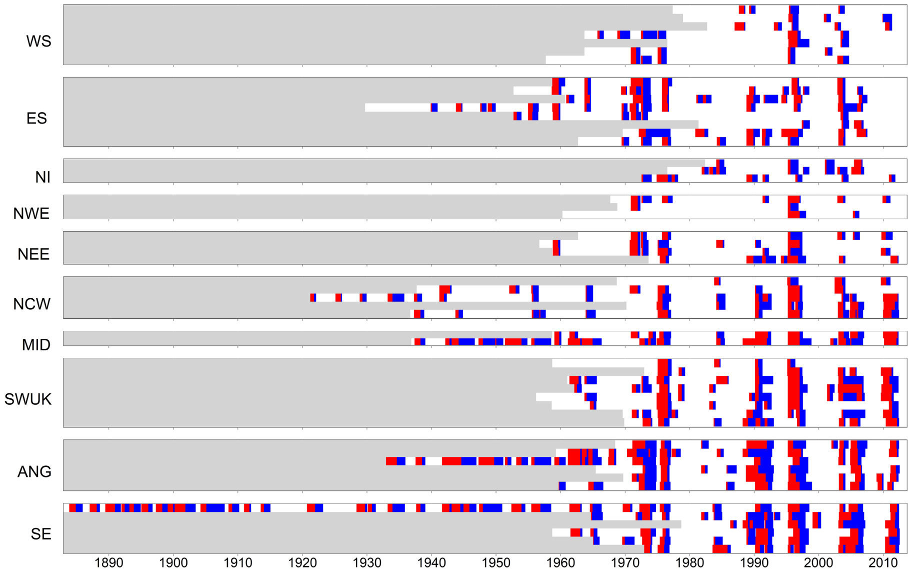


**Figure 3.** Period of record chronologies of drought termination for all 52 study catchments. Red bars indicate drought development, blue bars indicate drought termination, white bars indicate no drought development or drought termination, and grey bars signify periods before gauged river flow records began. Regions are denoted as follows: WS = Western Scotland; ES = Eastern Scotland; NI = Northern Ireland; NWE = North-west England; NEE = North-east England; NCW = North and Central Wales; MID = Midlands; SWUK = South-west United Kingdom; ANG = Anglian; SE = Southern England.





HESSD
doi:10.5194/hess-2015-476



Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

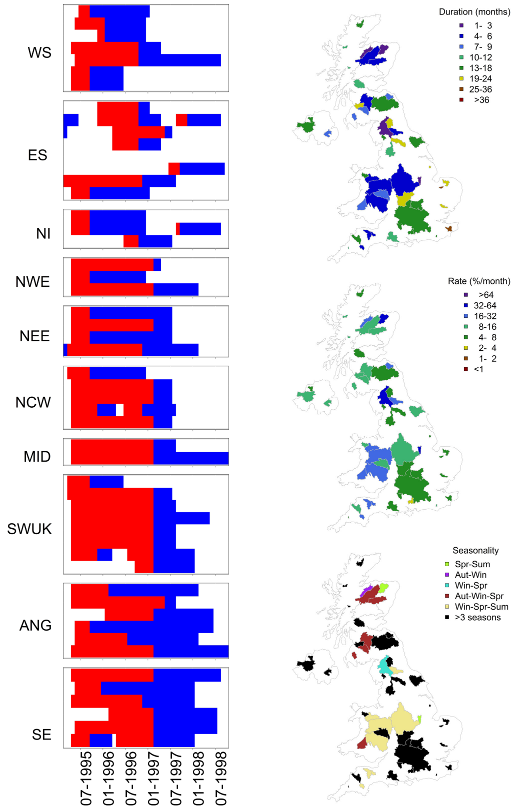


**Figure 4.** The 1995–1998 drought termination: chronologies of drought development and drought termination (left); drought termination duration (top right); drought termination rate (middle right); drought termination seasonality (bottom right). Regions are denoted as follows: WS = Western Scotland; ES = Eastern Scotland; NI = Northern Ireland; NWE = North-west England; NEE = North-east England; NCW = North and Central Wales; MID = Midlands; SWUK = South-west UK; ANG = Anglian; SE = Southern England.





HESSD
doi:10.5194/hess-2015-476



Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀ | ▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

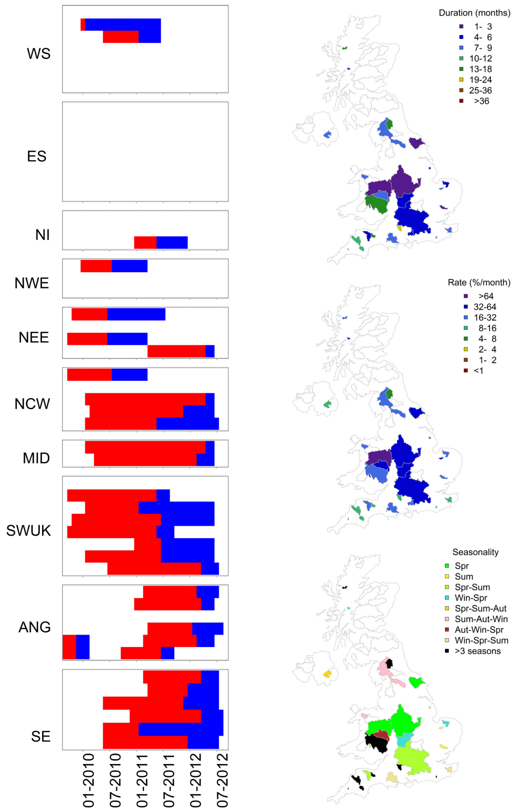


**Figure 5.** The 2009–2012 drought termination: chronologies of drought development and drought termination (left); drought termination duration (top right); drought termination rate (middle right); drought termination seasonality (bottom right). Regions are denoted as follows: WS = Western Scotland; ES = Eastern Scotland; NI = Northern Ireland; NWE = North-west England; NEE = North-east England; NCW = North and Central Wales; MID = Midlands; SWUK = South-west UK; ANG = Anglian; SE = Southern England.





HESSD
doi:10.5194/hess-2015-476

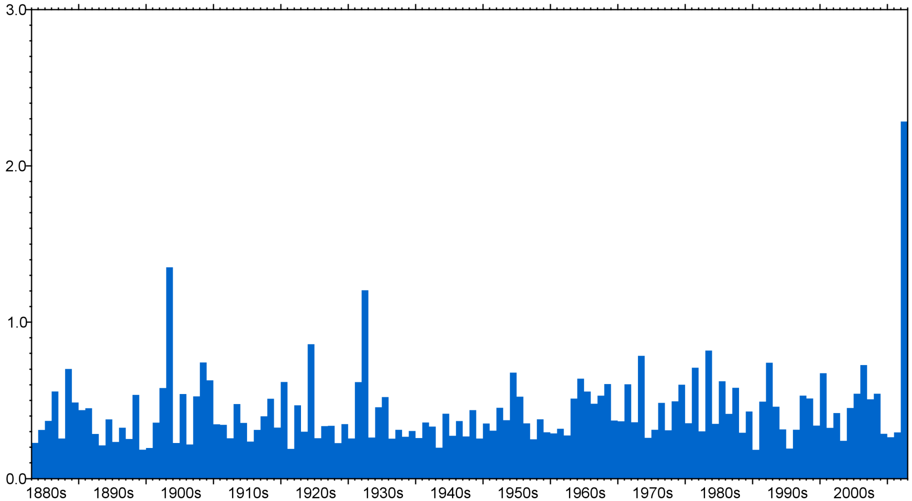


**Figure 6.** Ratio between average naturalised river flows for May–July and the preceding January–March for the Thames at Kingston (from Marsh et al., 2013).





HESSD
doi:10.5194/hess-2015-476

A systematic assessment of drought termination in the United Kingdom

S. Parry et al.