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Persistence of hydrometeorological droughts in the United Kingdom: A regional analysis of multi-season rainfall and river flow anomalies

Wilby[1], R.L., Prudhomme[1,2], C., Parry[1,2], S., Muchan[2], K.G.L.

[1] Department of Geography, Loughborough University, LE11 3TU, UK

[2] Centre for Ecology & Hydrology, Wallingford

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Corresponding author: Robert Wilby (email: r.l.wilby@lboro.ac.uk)

Abstract

This paper investigates the spatial and temporal properties of persistent meteorological and hydrological droughts in the UK at national to sub-regional scales. Using 1961-1990 as the reference period it is shown that the longest observed run of below average rainfall since the 1870s persisted for four years in northern England and parts of Scotland during 1892-1896. The longest observed run of below average discharge since the 1950s/1960s was found for some groundwater fed rivers in the English lowlands and lasted up to 5.5 years during 1988-1993. Distributions of dry-spell lengths were represented by a Markov model fit to each rainfall and discharge record. This model provides a good fit to observed geometric distributions of spell lengths and provides credible runs of below average river flows lasting up to a decade in some vulnerable catchments in southern England. Droughts of this persistence may not yet have occurred within the instrumented record but could have profound water management implications for the region. Predicted 100-year drought durations for catchments in northern England may not be as long but could have serious ramifications for surface water supplies. These findings point to a risk of irreversible drought impacts on aquatic communities that are simultaneously stressed by unsustainable abstractions, poor water quality and/or habitat modifications.

Key words: Drought duration; Markov model; homogeneous rainfall region; reconstructed river flow.

1. Introduction

Severe multi-season droughts are a recurrent feature of the UK hydroclimate. Runs of unusually dry winters and summers occurred repeatedly within the 1880s, 1890s and 1900s, and in the years 1920-1922, 1933-1934, 1943-44, 1975-1976, 1988-1992, 1995-1997, 2004-2006, and 2010-2012 (Marsh et al. 2007; Parry et al. 2013). Such episodes place water supplies under immense stress as competing needs of society, agriculture, commerce and the environment must be reconciled. With high demand, relatively low rainfall, high evaporation and high dependence on groundwater resources, south east England is particularly vulnerable to long duration droughts. A widely held view is that this region is susceptible to water supply problems after just three dry winters in a row (Duan et al. 2013). Not surprisingly, there is considerable interest in understanding the links between dry-spells, atmospheric circulation patterns, ocean temperatures and hence the seasonal predictability of European droughts (e.g. Colman and Davey 1999; Wilby, 2001a; Lloyd-Hughes and Saunders 2002; Wedgbrow et al. 2002; 2005; Wilby et al. 2004; Svensson and Prudhomme 2005; Folland et al. 2015; Kingston et al. 2015).

This paper addresses two important questions. First, what are the regional variations in likelihood of long duration hydroclimatic droughts in the UK? Second, what is the longest continuous period of below average precipitation and/or river flow that is conceivable in the UK under present climate variability? Answers to these two questions are pertinent to the design of systems with large storage capacity; whereas the prediction schemes mentioned above are relevant to the operational management of such water supply infrastructure. In either case, analysis of the characteristics and drivers of long-lasting UK droughts is tractable thanks to the growing availability of observed and reconstructed, multi-decadal rainfall-runoff indices (e.g. Alexander and Jones 2001; Barker et al 2004; Bayliss et al 2004; Jones et al 2006; Burt and Howden 2011; Wilby and Quinn 2013; Hannaford 2015).

Previous studies have evaluated the probability and return period of droughts using a range of statistical methods and descriptors of drought characteristics (Dracup et al 1980). For example, Gupta and Duckstein (1975) modelled the occurrence of extreme droughts as a Poisson process; Jackson (1975) represented drought lengths using a Markov mixture model. Here, we are particularly interested in the persistence of droughts and note the widespread representation of drought lengths as a geometric distribution (e.g. Kendall and Dracup 1992; Mathier et al. 1992; Sharma 1996; 1997; Bayazit et al 2005; Vargas et al. 2011). This involves making (arbitrary) decisions about threshold conditions for drought onset and termination which, in turn, define individual dry-spells. Homogeneity and stationarity of the underlying rainfall-runoff series must also be assumed.

The next section introduces the rainfall and runoff records used in our analysis of long duration droughts in the UK. This is followed by a description of the statistical methods used to identify runs of above and below average rainfall-runoff, then to generate synthetic sequences of wet- and dry-spells from which likelihoods of persistent drought can be assessed. We use this evidence to address our questions about the extent of regional variations and duration of the most persistent droughts. We then discuss some of the hypothesized causes and consequences of multi-year droughts for the UK water sector, and consider the extent to which our drought diagnostics might be applied to other information sources such as climate model output or reconstructed river flows. Finally, we distil our headline findings and offer suggestions for further research.

2. Data

Our analysis draws on three data sets. First, monthly precipitation totals (mm) for the nine homogeneous rainfall regions of the UK (Figure 1a), England and Wales (EWP) and Scotland (SP) were obtained from the Met Office Hadley Centre. The EWP series begins in 1766, the regional series in 1873, and Scotland, Scottish sub-regions and Northern Ireland in 1931. All series are based on long-running meteorological stations that are weighted to provide homogeneous, area-averaged precipitation totals (Alexander and Jones, 2001). The records are updated every six months.

Second, monthly reconstructed precipitation totals (mm) for the Central English Lake District (CELD) were taken from Barker et al. (2004) for the period 1806-2000. Data are available from 1788 but 1806 is the first year of the unbroken record. The CELD series is an index of precipitation hindcast from several fragmented rainfall records that have been statistically bridged to data from a long-running station near Grasmere. The index is highly correlated with the homogeneous rainfall region series for NWE (r=0.82), inflows to Lake Thirlmere (r=0.85) and the winter North Atlantic Oscillation Index (r=0.61). Hence, CELD provides earlier data to supplement the NWE series, as well as a means of assessing wet- and dry-spell simulation at sub-regional scales for a strategically important surface water supply area.

Third, monthly mean discharge (m^3 s^{-1}) series were extracted from the National River Flow Archive (NRFA) for 23 UK catchments (Figure 1b). Some stations form part of the National Hydrological Monitoring Programme (NHMP) and were selected because of their longevity, homogeneity and relevance to operational drought management. Others overlap with the network of 15 reference stations used by Jones et al. (2006) to reconstruct river flows from rainfall back to the 1860s, and by Wilby (2006) to search for early signals of climate change in summer low flows. Collectively, these catchments provide good geographic coverage of the UK whilst reflecting a range of geologies, elevations and climate regimes. However, it is important to stress that flow naturalization has not been applied to any of the 23 records analysed herein. This means that low flows reflect the combined effect of hydroclimatic conditions and water management decisions during periods of rainfall deficit.

The earliest observed river flows used in the present analysis begin in 1929 (Dee), 1935 (Derwent), 1936 (Wye) and extend to present (2013). We define Tier 1 catchments as those with unbroken records covering at least the baseline period 1961-1990; Tier 2 catchments begin after 1961 but have at least 35 years of data. The Ely Ouse record covers the years 1958-2013 but is treated as a Tier 2 catchment because of concerns about the homogeneity of the observed series since the mid-1980s (Jones et al., 2006). Likewise, there are doubts about the homogeneity of the Eden record in the 1960s and 1970s. Hence, results for the Ely Ouse and Eden provide insight to the robustness of Markov modelling approaches in cases where the flow regime is known to be heavily modified.

Methods

The homogeneous rainfall and river flow series were processed in four steps. First, mean monthly rainfall totals and discharge were calculated for the baseline period 1961-1990. These averages were consolidated into mean winter (October to March) and summer (April to September) half year rainfall totals and discharge. Seasonal anomalies were then calculated for the entire length of each series using their respective 1961-1990 half-year means, recognising that wet- and dry-spell lengths are sensitive to these arbitrary baselines (Sen, 1980). Any missing monthly values were replaced by the corresponding mean monthly value.

Second, conditional dry-to-dry (Pdd) and wet-to-wet (Pww) Markov model transition probabilities were derived for each series of seasonal anomalies. This was achieved by counting the frequency with which a dry (below average) season is followed by another dry season. Pdd is then the fraction of transitions that are dry-to-dry relative to all transitions (i.e. dry-to-dry and dry-to-wet). Pww was calculated in the same way for transitions from wet (above average) seasons. The length of each continuous dry- and wet-season run was also recorded in order to construct frequency distributions of spell lengths and to extract the most persistent episodes on record. In a subsidiary analysis, Pdd and Pww were computed using 30-year moving blocks of the seasonal precipitation series to detect any underlying trends in dry- and/or wet-spell persistence. Note that the discharge series were deemed to be too short to perform the same diagnosis.

Third, following Wilby (2007) and Sharma and Panu (2012; 2014a;b), observed Pdd and Pww transition probabilities were used to stochastically generate synthetic series of seasons with above or below average rainfall/discharge. A single 10,000 season Markov model simulation was undertaken in order to produce a cumulative distribution of synthetic spell lengths. The two-sample, nonparametric Kolmogorov-Smirnov (KS) test was used to assess whether the maximum discrepancy (Dstat) between observed and simulated cumulative distributions of spell-length was significantly ($p<0.05$) different.

Finally, a boot-strap, Markov model simulation was performed to generate multiple realisations of 100 year (i.e. 200 season-long) sequences for each rainfall and river flow station. Maximum dry- and wet-spell lengths were stored then the next simulation was run. This process was repeated 1000 times in order to build a distribution of synthetic 100-year wet- and dry-spells to compare with the longest observed dry and wet runs. The 100-year event was chosen because this return period is comparable with the available record lengths and would be expected to cause significant water supply problems. Although drought of this severity exceeds the return period used by even the most precautionary water companies for temporary water use bans (Table 1) century scale events are applied in supply-demand analysis and in company Water Resource Management Plans (e.g. Spraggs et al. 2015).

3. Results

Figure 2a shows seasonal anomalies as percentages of the 1961-1990 mean for EWP since 1766. Overall, the maximum single wet-season anomaly was +83% in the summer of 1782 (followed by +65% in summer 2012). A maximum single dry-season anomaly of -48% occurred in winter 1784/85 (followed closely by -47% in winter 1879/80). In general, 97% of single season anomalies fall within the range ±40% of the 1961-1990 mean. Other notable features include the previously reported runs of exceptionally wet years in the 1870s (Burt et al., 2014), dry years in the 1850s (Barker et al., 2004) and at the end of the nineteenth century (Marsh et al., 2007). Persistent dry-spells are also evident in the 1770s and 1780s but these have received relatively little attention to date. Figure 2b shows in greater detail the anomalies for the sub-period 1961-2014 which included the intense three season drought of 1975/76 and four season droughts of 1971-1973, 1995-1997, 2004-2006 and 2010-2012. Figure 2a shows the longer-term variability within which these most recent drought episodes sit, pointing to the futility of trend estimation based on hydrometric records that typically begin in the dry 1970s (Murphy et al., 2013).

Despite the simplicity of the seasonal anomaly metric, the index captures some well-known dry-spells. For example, Figure 3 shows the so-called 'Long Drought' of 1890-1910 which was initiated and sustained by sequences of notably dry winters but punctuated by a few very wet interludes such as 1903 (Marsh et al., 2007). During this 20 year period 68% of the half-year seasons accrued rainfall totals less than the 1961-1990 mean in SEE and NEE. Comparing the two regions reveals synchronicity in the persistence of the drought but spatial variation in local rainfall anomalies. Overall, the longest unbroken run of dry half-years in the EWP series lasted 8 seasons (i.e. 4 years) between the years 1812-1815. Eight season droughts have also occurred in NEE (1892-1896), SS (1970-1974) and NS (1975-1978).

Table 2 shows the conditional Pdd and Pww values for each homogeneous rainfall region as well as the longest observed dry- and wet-spell. Pww exceeds Pdd in all regions (except NEE and EWP) and this is reflected by the durations of longest wet- and dry-spells in observed rainfall. To date, four regions (SEE, SWE, CEE and ES) and Scotland have not experienced dry-spells lasting longer than 6 seasons. However, in the case of ES and Scotland, the observed 6 season drought is actually longer than the 100-year event (i.e. ~5 seasons) predicted by the model for these two regions. Overall, NEE has experienced the longest observed wet-spell which lasted 10 seasons (1965-1969).

Analysis of the temporal variability in Pdd and Pww reveals significant ($p<0.05$) trends towards more persistent wet-spells but less persistent dry-spells in EWP since records began (Figure 4). In fact, the present (to 2014) 30-year Pww is close to the maximum wet-spell persistence observed at the turns of the nineteenth and twentieth centuries. Rainfall records are much shorter for Scotland and Ireland than EWP. However, the former shows a tendency towards increased wet-spell persistence, whilst the latter exhibits more durable dry-spells. Closer inspection of the regional signatures of Pdd reveals statistically significant long-term declines for SWE, CEE, NWE and NEE, although SWE has experienced a noticeable upturn in the most recent 40 years (Figure 5). Such findings must be interpreted with care because of multi-decadal variations in Pdd but the recent persistence of dry-spells in NEE and NWE is approaching the lowest level since the 1870s. Overall Pdd for EWP is most strongly correlated with Pdd for CEE ($r=+0.77$) and SS ($r=-0.74$), albeit for a shorter record. SEE is currently the region with greatest seasonal dry-spell persistence.

At the scale of England and Wales, Scotland and Northern Ireland, more than 60% of dry-spells last a single season (half-year) (Figure 6). The Markov model consistently under-estimates the likelihood of single season spells but over-estimates the chance of two- and three season spells. Nonetheless, the KS test indicates that a null hypothesis of no difference between observed and simulated rainfall cannot be rejected (at $p<0.05$) for any of the dry-spell length distributions shown in Figures 6 and 7. Likewise, there are no statistically significant differences between observed and simulated wet-spell distributions (not shown). These results suggest that the first-order Markov model provides a good approximation of observed wet- and dry-spell lengths for rainfall anomalies at sub-regional (Lake District), regional and national scales in the UK.

Markov model dry-spell length distributions for river flow anomalies are also statistically indistinguishable from observations (Figure 8). Although the Dstat is less than the critical value, relatively large discrepancies (Dstat>0.10) are noted for six catchments: Findhorn (dry-spell); Tyne (wet-spell); Wensum (dry- and wet-spell); Itchen (wet-spell); Dee (Wales) (wet-spell); and Nith (dry- and wet-spell). In the case of the Findhorn, Wensum and Nith there was a greater than expected frequency of dry-spells lasting 6 seasons or longer (Figure 8). Conversely, the closest matches between simulated and observed wet- and dry-spell lengths were found for the Dee (Scotland) and Wye.

With the above capabilities in mind, the Markov model was run 1000 times each for 100 year simulations to build a synthetic distribution of century-scale dry- and wet-spell durations for rainfall (Table 2 and Figure 9) and discharge (Table 3 and Figure 10). A tendency for longer wet- than dry-spells of rainfall is reflected in the probability distributions for maximum 100-year episodes (Figure 9). Across all regions the very longest 100-year dry-spell generated by the model ranged from 10 (ES) to 22 (NS) seasons. However, the central estimates were 4.9 and 8.2 seasons respectively, consistent with the observed maximum lengths. In fact, all observed maximum dry-spells lie within the 95% confidence intervals of the bootstrap results for the simulated 100-year drought duration.

Nine out of 15 Tier 1 catchments have a tendency for longer low- than high-flow spells (Table 3) counter to regional rainfall (where wet-spell length typically exceeds dry-spell length). This difference is most marked in the Wensum and Medway where the central estimate 100-year hydrological drought persists for ~11 seasons (Figure 10). As with rainfall distributions, all observed maximum low-flow spells lie within the 95% confidence intervals. However, simulated likelihoods of exceedance of observed maximum duration droughts are greatest in the Thames ($p=0.78$), Medway ($p=0.92$) and Itchen ($p=0.90$). In other words, according to the Markov model, there is high confidence that observed discharge records for these catchments (dating from the 1950s and 1960s) do not yet contain a 100-year drought. Note also the long tails for dry-spells in the Wensum and Medway (Figure 10) where the model suggests the possibility of a 100-year event lasting 20-seasons (i.e. 10-years) with likelihoods p=0.007 and p=0.012 respectively.

Figure 11 shows the geographic distribution of simulated 100-year low- and high-flow durations for all catchments. The southeast to northwest gradient in simulated low-flow durations broadly reflects the distribution of major aquifers, annual precipitation totals and evaporation. The pattern for high-flow spells is more heterogeneous but there is a weak positive correlation between Tier 1 catchment area and simulated high-flow duration. As conceded from outset, none of the 23 flow records have been naturalised; all reflect to varying degrees the combined signals of hydroclimatic variability and water management particularly during arid periods.

4. Discussion

We have investigated the spatial and temporal properties of long-lasting hydrometeorological droughts in the UK at various scales and half-year granularity. Using 1961-1990 as the reference period it is shown that the longest observed run of below average rainfall since the 1870s persisted for 8 seasons (i.e. 4 years) in northern England and parts of Scotland. There is evidence of increased persistence of dry-spells in EWP since the 1980s but this must be seen in the context of an overall decline and multi-decadal variability since the 1760s. The longest observed run of below average flow since the 1950s and 1960s was found for groundwater fed rivers in the English lowlands and lasted up to 11 seasons (i.e. 5.5 years) in the Wensum. Longer drought durations for river flow than rainfall reflect the combined effect of evaporative losses and serial correlation on low flow sequences. Moreover, above average summer precipitation may be insufficient to replenish large accumulated soil moisture deficits and thereby terminate a hydrological drought (Parry et al. 2015).

Consistent with previous studies we find that first-order Markov models provide a good approximation of the distributions of seasonal drought duration at national, regional and sub-regional scales (Bayaz and Önöz, 2005; Mathier et al., 1992; Sharma and Panu, 2014). When compared using the KS test, observed and simulated spell-length distributions were found to be statistically indistinguishable for all rainfall regions and river catchments. This gives some confidence in the realism of the same models for exploring expected durations of the 100-year drought, as well as likelihood of events lasting longer than previously captured by historic records of rainfall and river flow. Even where the flow regime is known to be heavily modified (e.g. Ely Ouse) the Markov model still replicated the net effect of hydroclimatic forcing and water management in the overall distribution of low-flow durations. Elsewhere, 'hands off' rules limit abstractions at times of low-flow (e.g. Itchen) so curtail this artificial influence on observed drought sequences (see Wilby et al., 2011).

Our Markov model simulations suggest that a dry-spell with 100-year return period may not yet have occurred within the instrumented flow record of some vulnerable catchments of southern (e.g. the Medway and Itchen) and northern (e.g. Tees) England. This is not entirely surprising. The hypergeometric distribution predicts that there is a 41% probability that the largest event in 100 years will *not* fall in a 59 year discharge series (see Arnell et al., 1990:43). Hence, an important implication is that the available flow record understates the persistence of rare droughts. Moreover, the statistical model suggests that a hydrological drought with 100-year return period could persist as long as a decade in some southern catchments. This raises questions about whether there might be analogues that have been documented prior to the era of continuous discharge measurement and whether such multi-year droughts are physically plausible. The long drought of 1890-1910 identified by Marsh et al. (2007) suggests that such events are indeed feasible.

Analysis of the long river flow record for the Thames provides evidence of near decadal-scale, low-flow epochs in the 1940s and 1900s (Folland et al., 2015). Even longer-term perspectives are given by river flow reconstructions. For example, Jones et al. (2006) show depressed flows across much of England and Wales in the period 1880-1900. Early droughts (lasting at least 36 months) based on rainfall reconstructions of runoff deficits have also been reported for the 1830s, 1850s, 1860s and 1890s in the Anglian region (Spraggs et al., 2015). Interestingly, the Anglian study found that flow simulations incorporating pre-1920s droughts actually showed increased yields at some reservoirs relative to yield estimates based on post-1920 flow data. This is because the post-1920 era captures the most severe droughts (1933-1936, 1943-1946, 1989-1992 and 1996-1998) and critical events used in Water Resource Management and Drought Plans even when data for 1798-2010 are available. The longest drought duration (based on dates of drawdown onset and full storage) at any of the reservoirs studied was 275 months at Covenham during 1989-2010.

It has long been suspected that warm and cold extremes of the El Niño/Southern Oscillation may be impacting the hydroclimate of northwest Europe (Fraedrich, 1990; 1994; Wilby, 1993; Lloyd-Hughes and Saunders, 2002). Furthermore, decade long shifts in rainfall and runoff in the UK could be linked to the Atlantic Multidecadal Oscillation (AMO) which describes variations in observed patterns of sea surface temperature (SSTs). For example, Wilby (2001b) found that positive SST anomalies in the North Atlantic are correlated with summer Pdd at stations across England and Scotland, implying increased drought persistence when the ocean is warm. Conversely, Sutton and Dong (2012) assert that recent anomalously wet summers in northern Europe are explained by a substantial warming of the North Atlantic since the 1990s. More recently, attention has focused on the association between La Niña episodes and winter rainfall deficits during major multi-annual drought episodes (Folland et al., 2015). The same study concluded that *no single driver convincingly explains the occurrence of any multi-annual drought in the historical record* (Folland et al., 2015: 12934). Hence, it seems that persistent droughts could be caused by interactions between near- (Atlantic) and far- (Pacific, stratospheric) field forcings. Kingston et al. (2015) further caution that the choice of drought index likely determines the inferred atmospheric driver(s). The lagged onset of hydrological drought behind meteorological drought is another factor to consider when evaluating potential drivers (Folland et al., 2015).

An 11 season low-flow spell in the River Wensum occurred between summer 1988 and summer 1993. This period was characterised by persistent anticyclonic blocking over Western Europe and southern England, with northern position of the jet stream leading to reduced frontal rainfall and exceptionally low groundwater levels in the English lowlands (Marsh et al., 2007). Locally, the drought could have lasted 20 seasons (i.e. 10 years) had there not been wet interludes in the winters of 1993/94 and 1994/95 raising the credibility of decade-long low-flow episodes in some rivers. The years 1988, 1989 and 1990 were also noteworthy at the time for being the warmest in the Central England Temperature series (Marsh and Monkhouse, 1993). Earlier drought periods in the 1970s were remarkable for the quiescence of summer cyclones (Matthews et al., 2015). Nonetheless, care must be taken when interpreting long-run, low-flow sequences because of their susceptibility to local artificial influences such as river regulation, effluent returns, water storage, or groundwater abstraction (in the case of the Wensum). Other meta-data are needed to augment flow records when evaluating homogeneity factors such as capability of the gauging station, impact of channel structures, river and land management practices (e.g. Marsh and Harvey, 2012).

Research into the riverine ecological consequences of multi-year droughts is hampered by the brevity of data sets in the UK. One detailed, multi-catchment assessment of the 1990-1992 and 1996-1997 droughts showed gradual decline then recovery of Lotic-Invertebrate Index for Flow Evaluation (LIFE) scores after the low flow period (Monk et al., 2008). Another study of the macroinvertebrate fauna of the River Lambourn during the extreme drought of 1976 found no evidence of loss of family richness but unusually high densities for some families, with rapid recovery at an unpolluted perennial site following drought termination (Wright and Symes, 1999). However, the recovery of invertebrate communities from much longer droughts is poorly understood and confounded by anthropogenic modifications to habitat and river flow (Bond et al., 2008). The so-called Millennium Drought in Australia, combined with water abstraction, provides insights to the impacts of a multi-decadal event. Some commentators speak in terms of 'regime shift' since the drought may have irreversibly degraded the natural capacity of many species and communities to recover to pre-event conditions (Davis et al., 2010). Such experiences underline the importance of identifying and protecting instream drought refugia.

We acknowledge that there is scope to refine some aspects of our Markov model. For example, slowly varying SSTs and/or the North Atlantic Oscillation (NAO) index could be used to condition the Pdd and Pww parameters rather than applying fixed values. This mixture modelling approach enables capture of both low frequency variations in dry- or wet-spell preponderance as well as seasonal variability in rainfall occurrence (e.g. Kiely et al., 1998; Wilby 2001b). We modelled drought duration independent of initial conditions or time of year whereas Vargas et al. (2011) showed that spell length (albeit based on daily precipitation records) depends on occurrence start date. Our present model version does not simulate drought intensity. Others have incorporated this capability by stochastically generating deficits using distributions such as the gamma (Kendall and Dracup, 1992), exponential (Mathier et al., 1992) or truncated normal (Sharma and Panu, 2014). The Markov model could also be fit to gridded rainfall observations (as in Rahiz and New, 2014) or climate model output to explore the spatial coherence of multi-year droughts under present and future climate conditions. Furthermore, the Pdd and Pww parameters are potentially useful diagnostics for verifying regional climate model realism.

Finally, there will be opportunities to apply the methodologies developed herein to river flow reconstructions currently being produced under the Historic Droughts and Water Scarcity Project (Hannaford *pers. comm.*). By drawing on a much larger set of long records with better coverage of the UK it will be possible to derive more detailed and robust assessments of spatial variations in the 100-year drought duration. Moreover, reconstructed river flows provide a means of scrutinising drought persistence without the confounding signals of abstraction and land-use change within low flow series (e.g. Jones et al. 2006). The NHMP stations may not reflect the natural behaviour of the catchment but they are monitored and data disseminated monthly as part of the network used to compile the national hydrological summaries. Hence, there will still be benefit of using the Markov method to calculate drought persistence indices at sentinel locations for long-term monitoring purposes.

5. Conclusions

This study used long homogeneous rainfall and river flow records to evaluate spatial-temporal variations in multi-year drought duration across the UK. We found that lengths of spells with below average (1961-1990) rainfall-runoff are well represented by a first-order Markov model which simulates transitions between wet- and dry-states. These models show that drought persistence is approximated by the geometric distribution, and predicts meteorological dry-spells with 100-year return period of 4 years in northern England and parts of Scotland and 100-year hydrological droughts of 5.5 years in the English lowlands. Furthermore, the same model provides credible evidence of the possibility of below average river flows lasting up to a decade in some groundwater fed catchments of southern England. Drought durations of this magnitude would have significant water management implications in a region where three dry winters in a row can be problematic. There is also a risk of irreversible drought impacts on aquatic communities that are simultaneously stressed by unsustainable abstractions, poor water quality and/or habitat modifications. Anthropogenic climate change adds further uncertainty about the ocean-atmosphere drivers and persistence of multi-year droughts in future decades.

Virtually all our Tier 1 catchments have experienced observed wet-spells longer than the simulated 100-year event, but nearly two thirds have not yet experienced observed dry-spells lasting longer than simulated the 100-year event. Attention is often focused on catchments in south-east England because of the fragility of the water supply-demand balance but other regions may also be vulnerable. For instance, observed discharge records for the Tees, Dee and the Wye have yet to include the estimated 100-year low-flow spell lasting 7, 8 and 9 seasons respectively. Water Resource Zones in northern England that rely heavily on surface supplies could be significantly impacted under these circumstances.

Our exploration of drought duration has opened several lines for further enquiry. Possible refinements to the Markov model include use of drought onset season as a conditioning variable; extension to multi-year drought *intensity* simulation; and incorporation of low-frequency forcing of model parameters using ocean-atmosphere indices. There is also scope for testing the realism of regional climate downscaling models at reproducing spell-length distribution of observed drought sequences. Recent studies of reservoir yield in eastern England suggest that droughts in the post 1920 era may be sufficiently severe for planning and design purposes. However, this assertion needs to be tested in other regions and for different configurations of water supply infrastructure. There also remain open policy questions about how best to manage the consequences of multi-year droughts on aquatic ecosystems, whilst taking into account the competing demands for water by society and the economy.

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Tables

Table 1 Level of service for Temporary Use Bans for largest UK water companies

Water Company	Level of Service	Water Company	Level of Service
Anglian Water	1 in 10yrs	Southern Water	1 in 10yrs
Bristol Water	1 in 15yrs	Thames Water	1 in 20yrs
Northern Ireland Water	Not relevant	United Utilities	1 in 20yrs
Northumbrian Water	Never	Welsh Water	1 in 20yrs
Scottish Water	1 in 40yrs	Wessex Water	1 in 30yrs
Severn Trent Water	3 in 100yrs	Yorkshire Water	1 in 25yrs
South West Water	1 in 20yrs		

Table 2 Observed conditional dry-to-dry (Pdd) and wet-to-wet (Pww) transition probabilities (persistence) for summer (April to September) and winter (October to March) half years (seasons) in homogeneous rainfall regions and the Central English Lake District (CELD). Observed maximum duration (seasons) dry and wet-spells are compared with simulated mean 100-year events.

Region	Period	Observed Persistence		Observed Maximum event		Simulated 100-year event	
		Pdd	Pww	Dry (seasons)	Wet (seasons)	Dry (seasons)	Wet (seasons)
SEE	1873-2014	0.500	0.550	6	8	6.7	7.8
SWE	1873-2014	0.489	0.500	6	7	6.9	6.9
CEE	1873-2014	0.518	0.541	6	7	7.3	7.7
NWE	1873-2014	0.496	0.514	7	9	6.8	7.1
NEE	1873-2014	0.492	0.489	8	10	7.0	6.8
EWP	1766-2014	0.464	0.445	8	7	6.5	6.2
SS	1931-2014	0.493	0.596	8	8	6.7	9.0
NS	1931-2014	0.568	0.593	8	9	8.2	8.6
ES	1931-2014	0.358	0.560	6	6	4.9	8.3
SP	1931-2014	0.366	0.521	6	8	5.0	7.4
NIP	1931-2014	0.397	0.461	7	8	5.5	6.4
CELD	1806-2000	0.513	0.505	8	7	7.1	7.0

Table 3 Observed conditional dry-to-dry (Pdd) and wet-to-wet (Pww) transition probabilities (persistence) for summer (April to September) and winter (October to March) half years (seasons) in selected rivers. Observed maximum dry- and wet-spell durations are compared with mean simulated 100-year events. Missing data were infilled using 1961-1990 monthly means. *Italics* show Tier 2 catchments with partial coverage of the baseline period 1961-1990.

River	Code	Water years	Observed Persistence		Observed Maximum event		Simulated 100-year event	
			Pdd	Pww	Dry (seasons)	Wet (seasons)	Dry (seasons)	Wet (seasons)
Findhorn	7002	1958-2013	0.442	0.491	7	6	7.0	6.0
Dee*	12001	1929-2013	0.407	0.505	5	7	5.6	7.2
Tyne*	23001	1956-2013	0.551	0.527	10	8	7.9	7.5
Tees*	25001	1956-2013	0.500	0.526	6	7	7.0	7.4
Wharfe	*27043*	*1974-2013*	*0.667*	*0.600*	*10*	*9*	*10.7*	*8.7*
Derwent	28085	1935-2013	0.625	0.587	11	11	9.7	8.4
*Ely Ouse***	*33035*	*1958-2013*	*0.742*	*0.638*	*13*	*11*	*13.7*	*9.5*
Wensum	34004	1960-2013	0.667	0.533	11	5	10.9	7.2
Thames	39008	1951-2013	0.635	0.600	7	8	9.7	8.8
Medway*	40003	1956-2013	0.667	0.511	7	6	11.0	6.8
Itchen*	42010	1958-2013	0.607	0.584	6	8	9.2	8.4
Exe*	45001	1956-2013	0.537	0.559	7	8	7.6	8.0
Wye*	55023	1936-2013	0.608	0.621	7	9	8.9	9.2
Teifi*	62001	1959-2013	0.468	0.567	5	11	6.2	8.3
Dee*	67015	1937-2013	0.539	0.533	7	9	7.7	7.5
Eden	76002	1960-1997	0.514	0.472	5	6	7.2	6.5
Eden	*76005*	*1965-2013*	*0.511*	*0.580*	*8*	*6*	*7.0*	*8.7*
Nith*	79002	1957-2013	0.449	0.581	5	9	6.0	8.6
*Cree**	*81002*	*1963-2013*	*0.481*	*0.447*	*5*	*7*	*6.7*	*6.1*
*Ewe**	*94001*	*1971-2013*	*0.452*	*0.463*	*5*	*7*	*6.3*	*6.4*
*Camowen**	*201005*	*1972-2011*	*0.419*	*0.630*	*6*	*15*	*5.6*	*9.9*
*Faughan**	*202002*	*1976-2013*	*0.694*	*0.417*	*9*	*7*	*12.0*	*5.4*
*Bush**	*204001*	*1972-2013*	*0.559*	*0.702*	*7*	*10*	*7.6*	*12.4*

* Stations in the NHMP ** Treated as Tier 2 because of the highly regulated flow regime

Figures

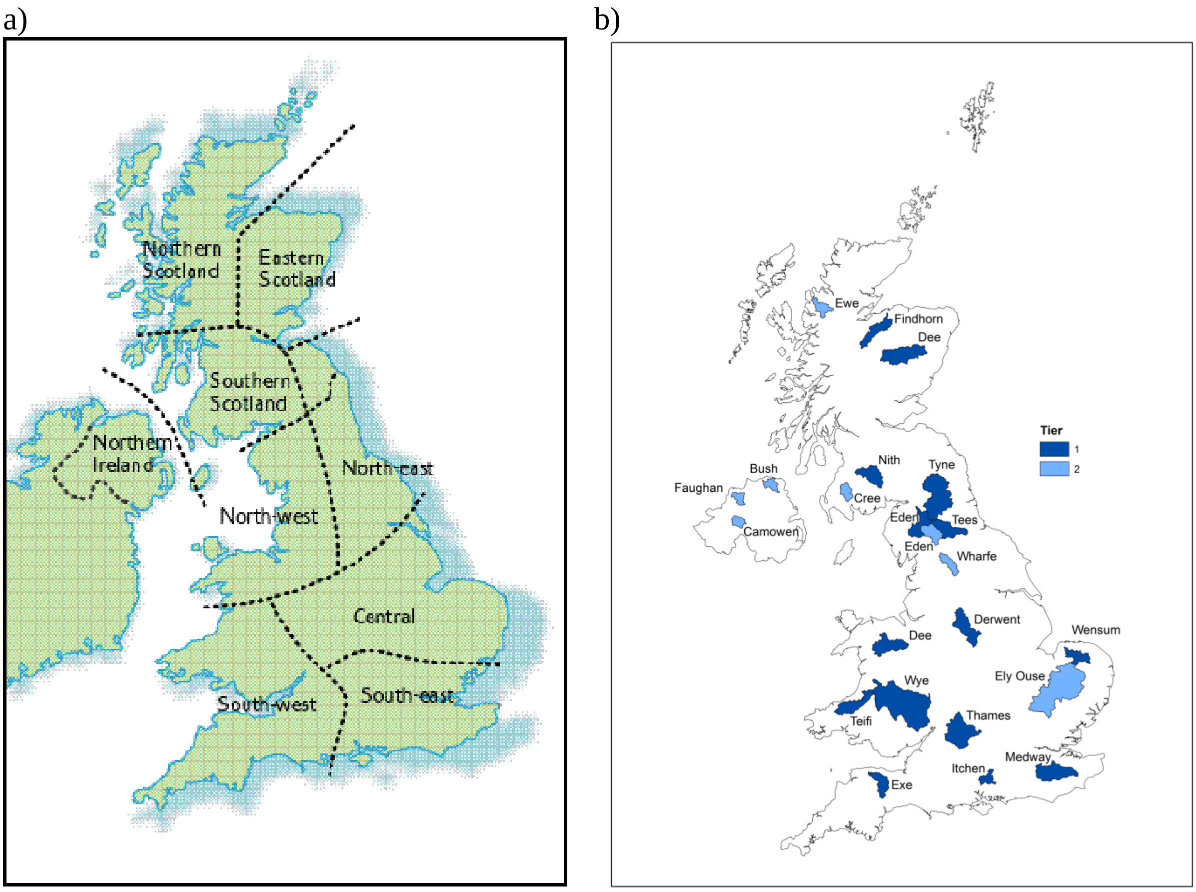
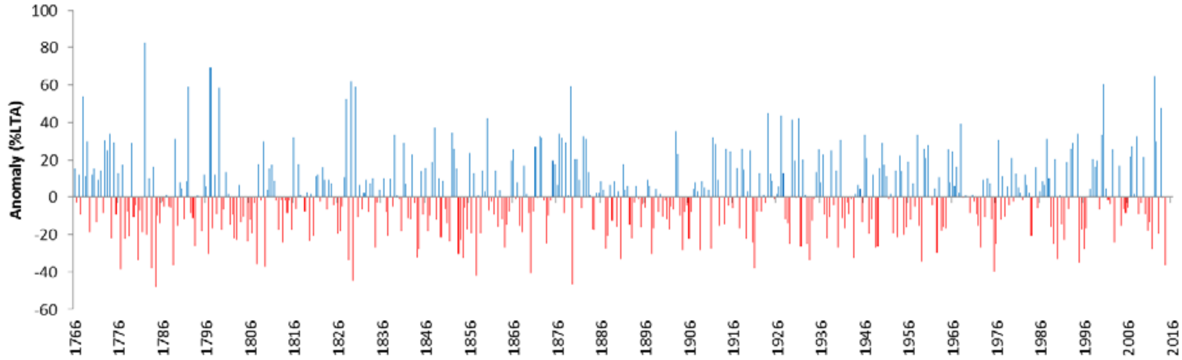


Figure 1 (a) Homogeneous rainfall regions of the UK: Southwest England (SWE), Southeast England (SEE), Central and Eastern England (CEE), Northwest England (NWE), Northeast England (NEE), Southern Scotland (SS), Eastern Scotland (ES), Northern Scotland (NS) and Northern Ireland (NI). Source: Met Office. (b) Tier 1 and Tier 2 river catchments used in the analysis of seasonal river flow anomalies.

a)



b)

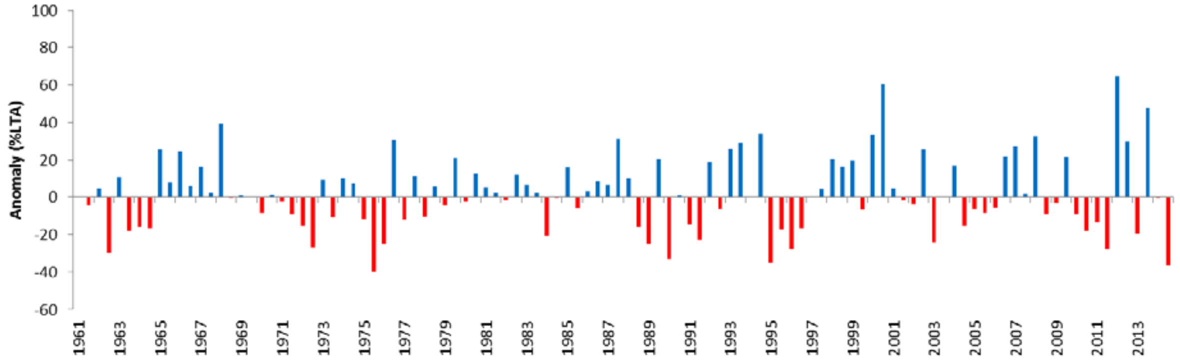


Figure 2 Above (**blue**) and below (**red**) long-term average precipitation totals in winter (October to March) and summer (April to September) half years (seasons) in England and Wales for years a) 1766-2014 and b) 1961-2014 (showing the detail of individual wet and dry sequences such as a four season dry-spell between 1995-1997). All deviations are expressed as percentage anomalies with respect to the 1961-1990 mean.

a)

b)

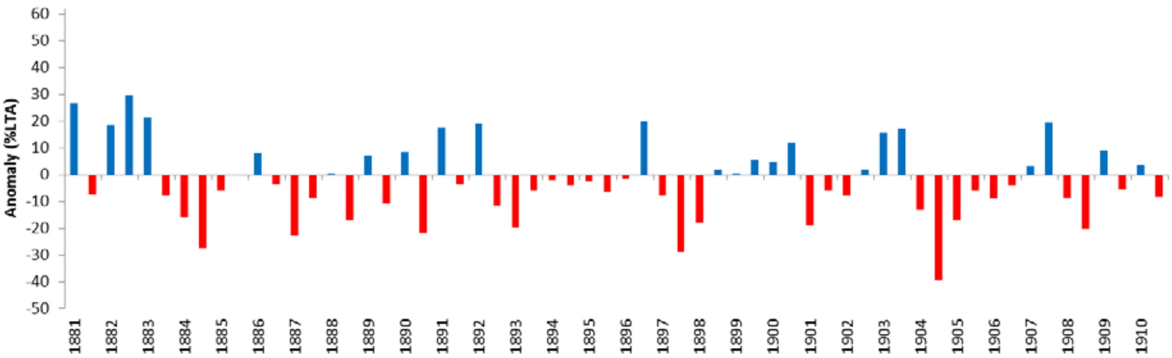
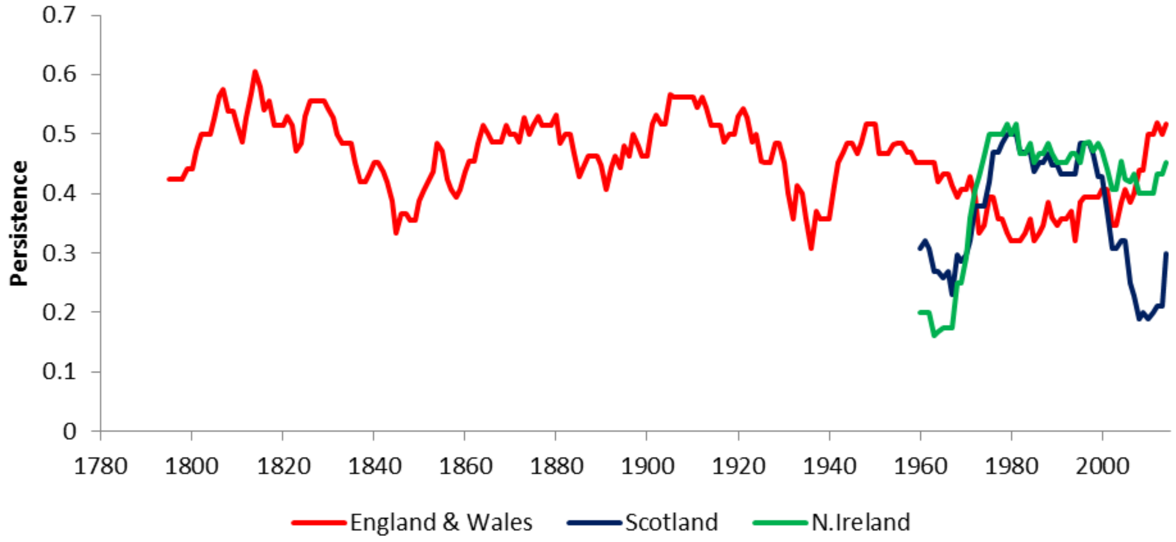


Figure 3 As in Fig. 2 but for a period of extreme dry-spell persistence in a) SEE and b) NEE. Deviations were calculated with respect to the 1961-1990 mean.

a)



b)

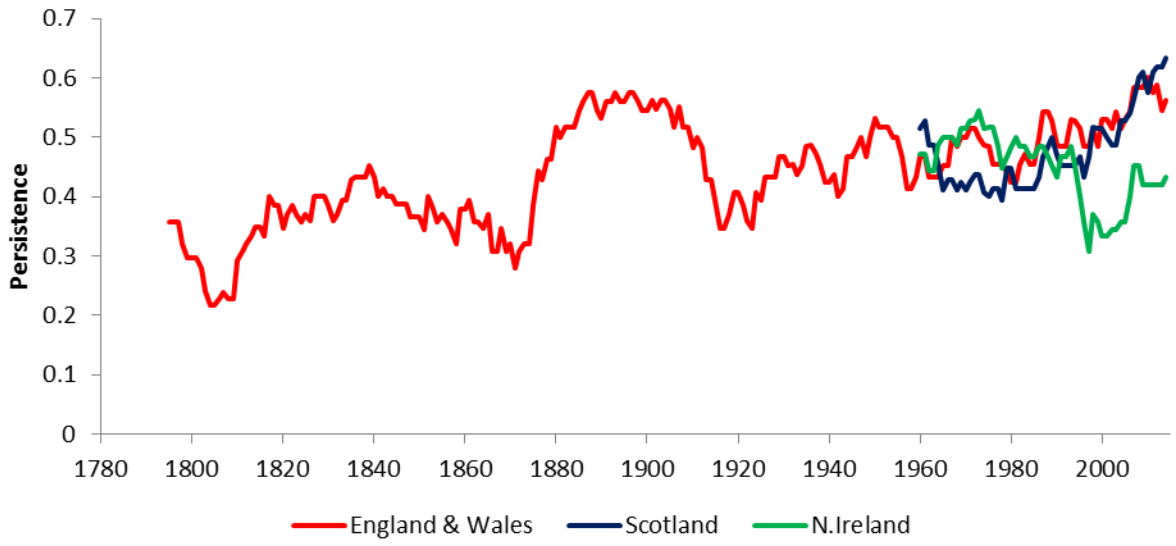
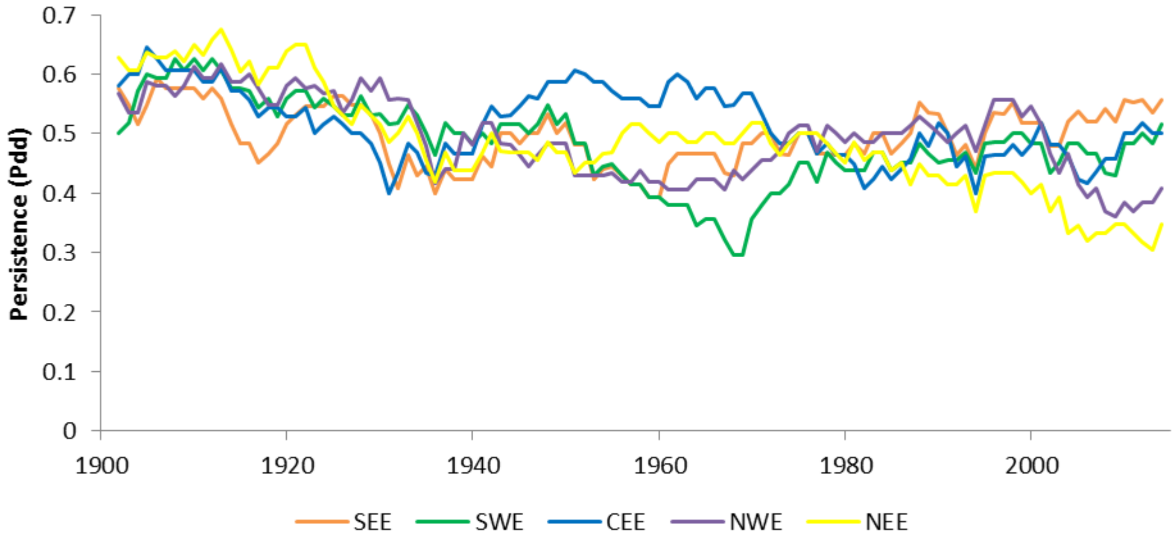


Figure 4 a) Dry-to-dry (Pdd) and b) wet-to-wet (Pww) season persistence for England and Wales, Scotland and Northern Ireland. All series are based on 30-year moving windows with anomalies referenced to the 1961-1990 mean.

a)



b)

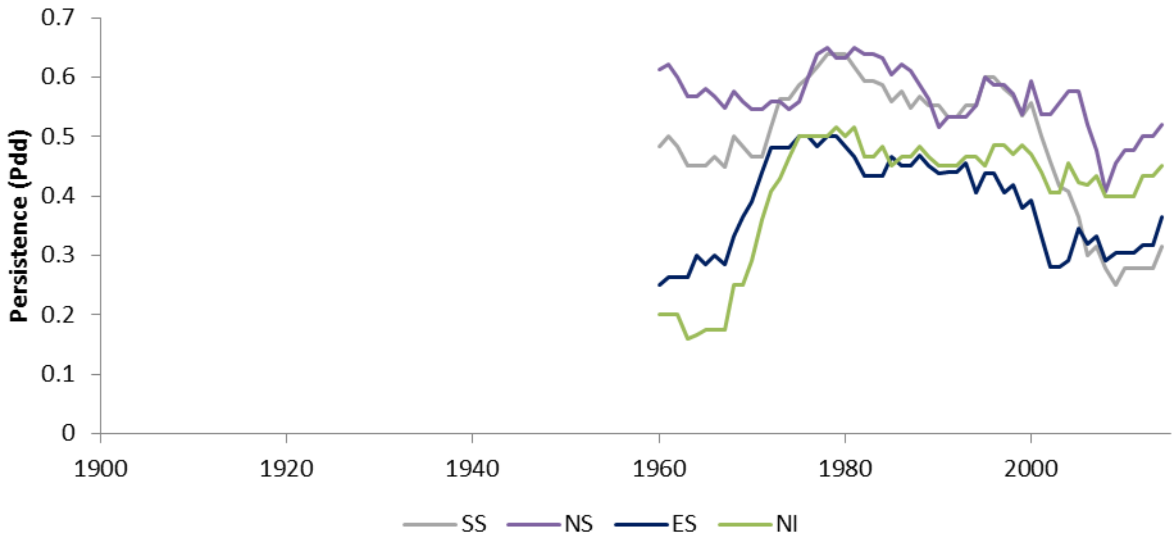


Figure 5 Dry-to-dry season persistence (Pdd) in the homogeneous rainfall regions of a) England and Wales, b) Scotland and Northern Ireland. All series are based on 30-year moving blocks with anomalies referenced to the 1961-1990 mean.

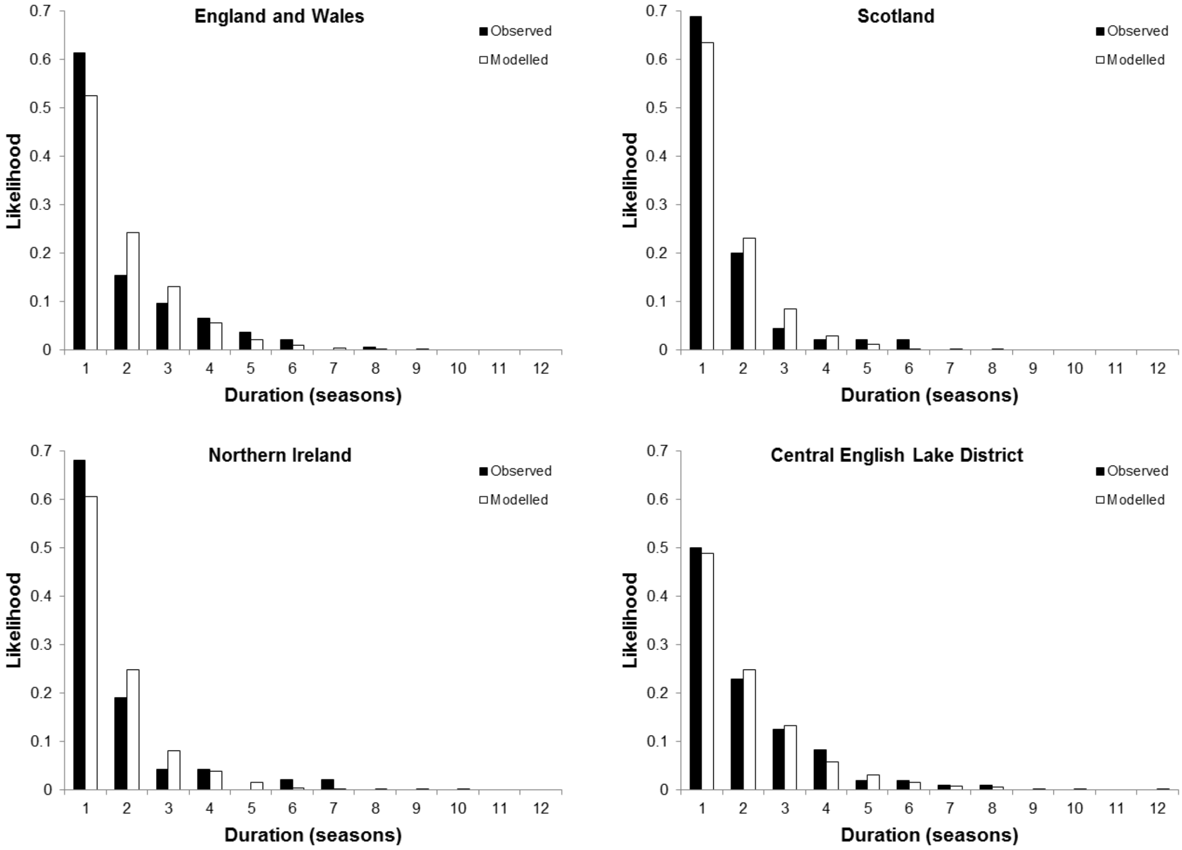


Figure 6 Observed and modelled likelihood of dry-spells of duration 1 to 12 seasons in England and Wales (1766-2014), Scotland (1931-2014), Northern Ireland (1931-2014) and the Central English Lake District (1806-2000).

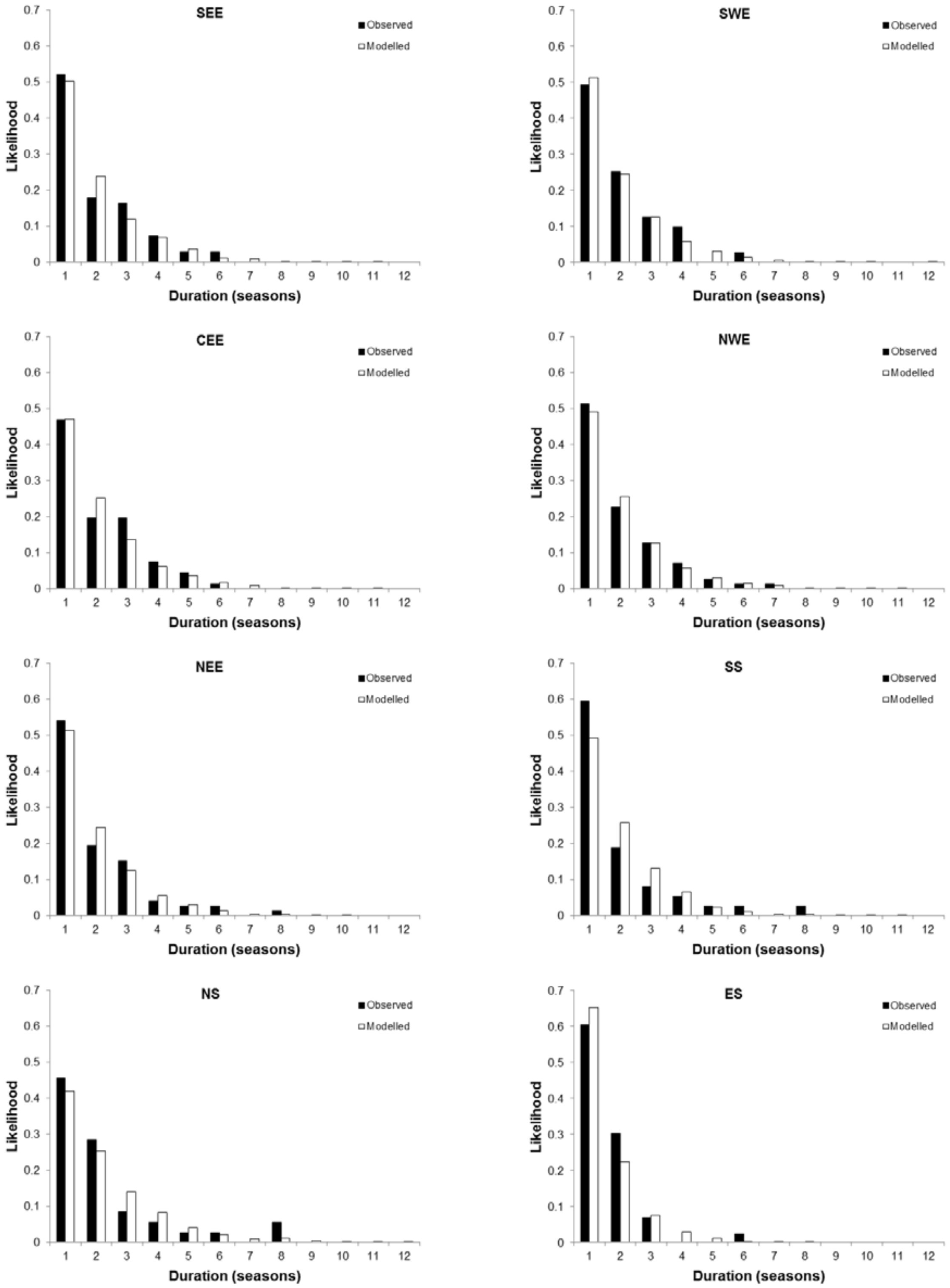


Figure 7 As in Fig.6 but for homogeneous rainfall regions of England, Wales and Scotland.

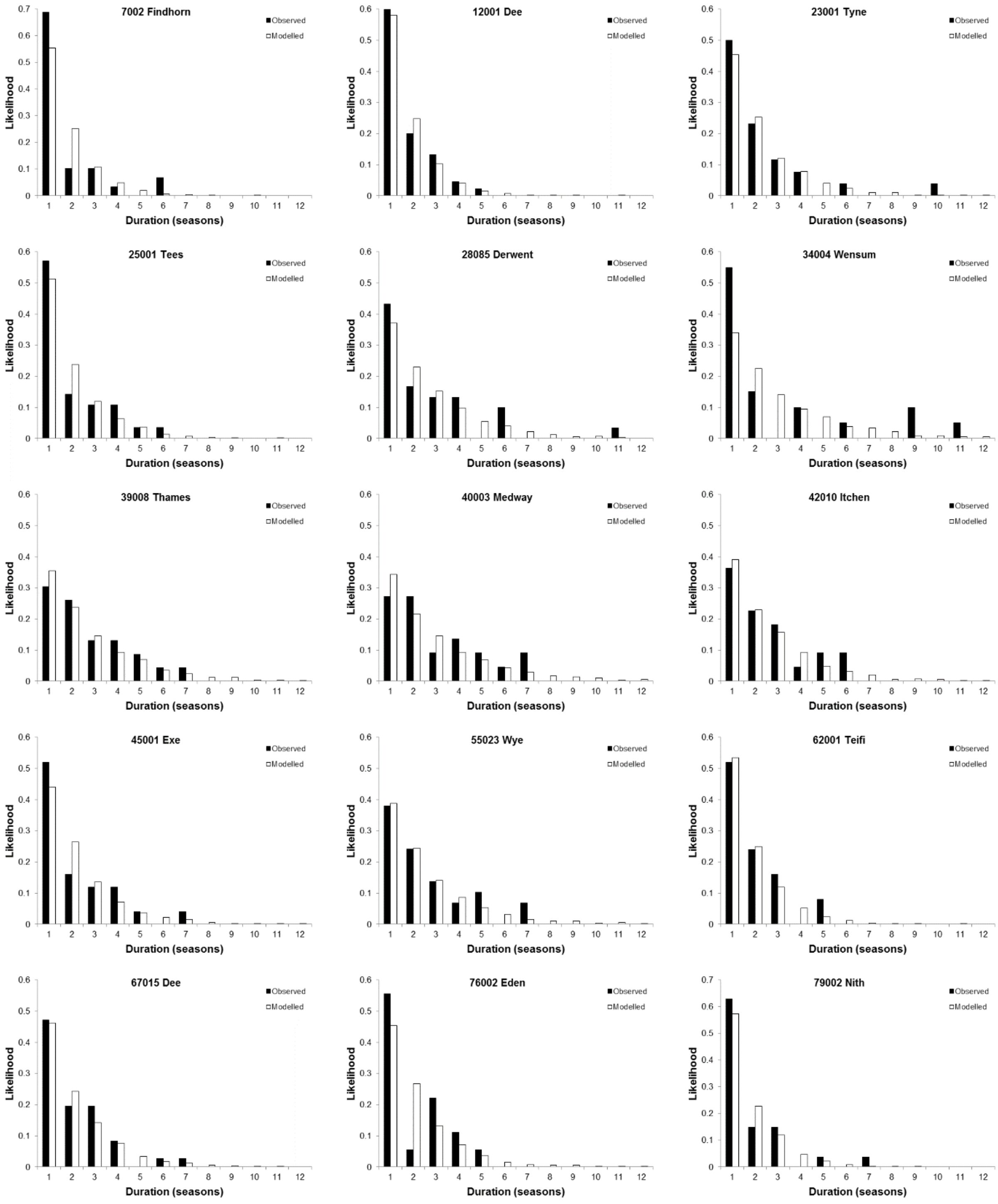


Figure 8 Observed and modelled likelihood of low-flow spells of duration 1 to 12 seasons for Tier 1 catchments. Note the different likelihood scale for the Findhorn and Nith; all other rivers have likelihoods <0.60 for a one season low-flow spell.

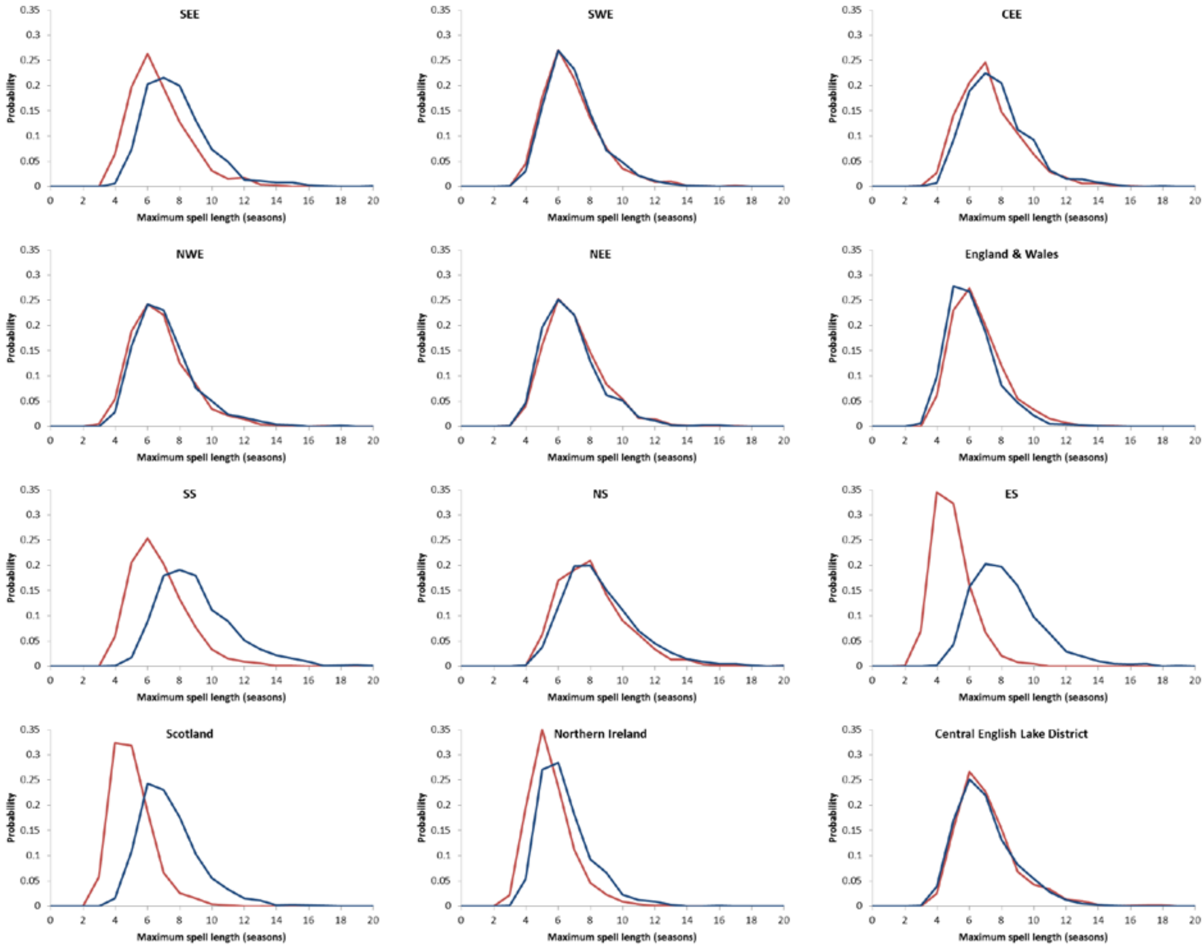


Figure 9 Probability distributions of maximum simulated 100-year dry- (red lines) and wet- (blue lines) spells in UK rainfall regions and the Central English Lake District index.

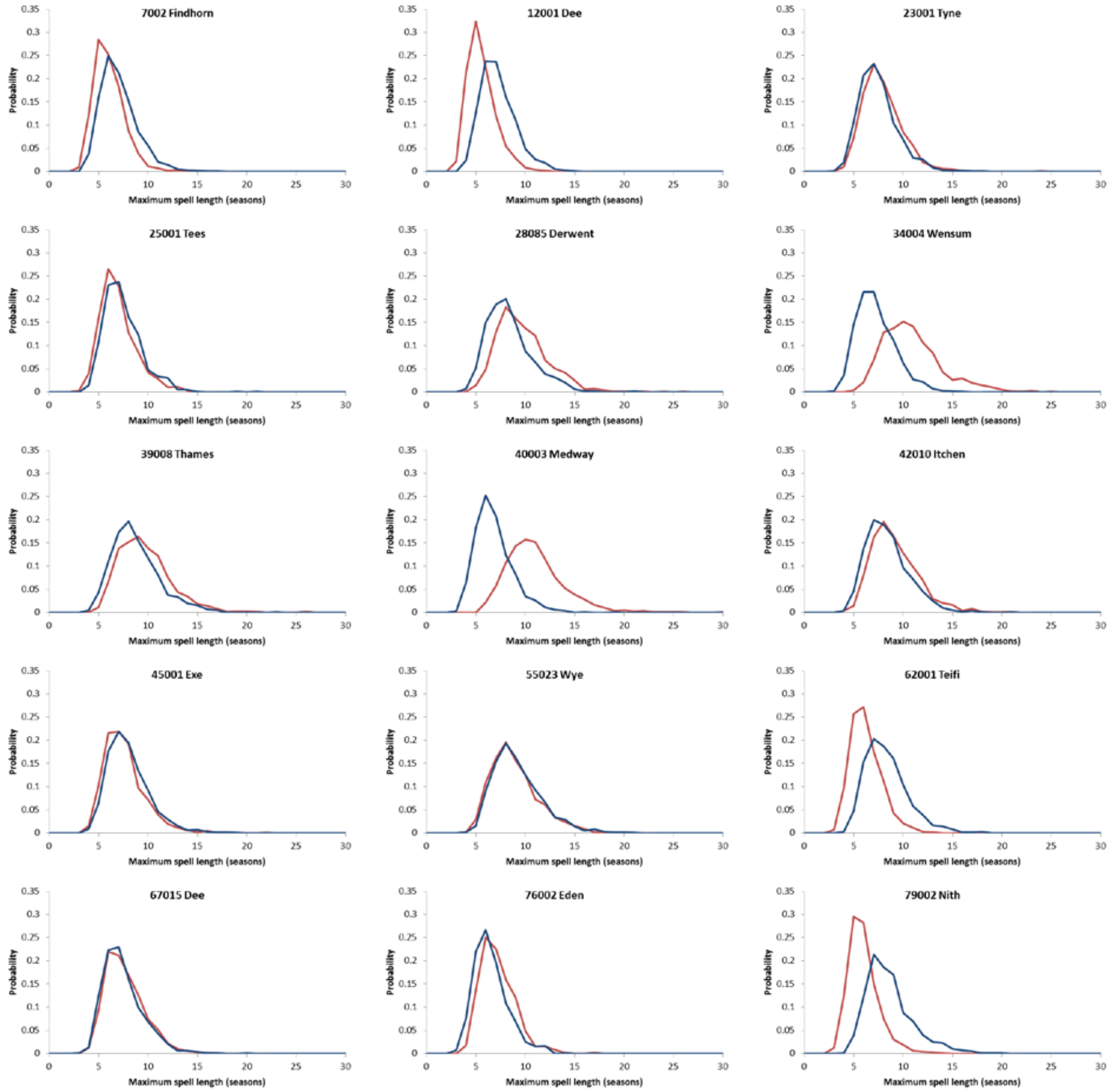


Figure 10 Probability distributions of maximum simulated 100-year low- (red lines) and high- (blue lines) flow spells in Tier 1 catchments.

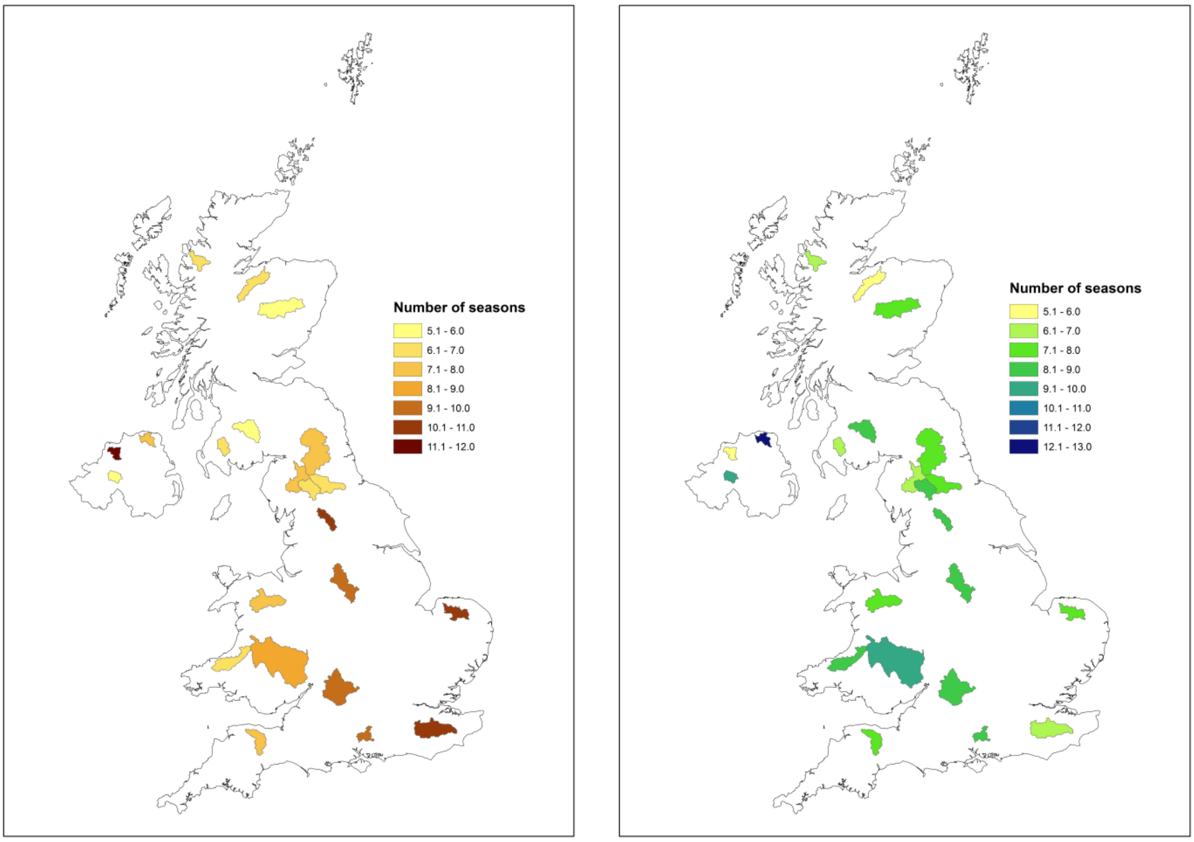


Figure 11 Simulated 100-year a) low- and b) high-flow spells for Tier 1 and 2 catchments. Note that the Ely Ouse is omitted because of known homogeneity issues.