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National-scale analysis of simulated hydrological droughts (1891-2015)

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Abstract

Droughts are phenomena that affect people and ecosystems in a variety of ways. One way to help with resilience to future droughts is to understand the characteristics of historic droughts and how these have changed over the recent past. Although, on average, Great Britain experiences a relatively wet climate it is also prone to periods of low rainfall which can lead to droughts. Until recently research into droughts of Great Britain has been neglected compared to other natural hazards such as storms and floods. This study is the first to use a national-scale gridded hydrological model to characterise droughts across Great Britain over the last century. Firstly, the model performance at low flows is assessed and it is found that the model can simulate low flows well in many catchments across Great Britain. Next, the threshold level method is applied to time series of monthly mean river flow and soil moisture to identify historic droughts (1891-2015). It is shown that the national-scale gridded output can be used to identify historic drought periods. A quantitative assessment of drought characteristics shows that groundwater-dependent areas typically experience more severe droughts, which have longer durations rather than higher intensities. There is substantial spatial and temporal variability in the drought characteristics, but there are no consistent changes through time.

Keywords

Drought severity, river flow modelling, low flow, soil moisture, drought characteristics, Great Britain

1 Introduction

Drought is a recurrent natural hazard that impacts many sectors, for example agriculture (rain fed and irrigated), ecosystems (terrestrial and aquatic), energy and industry (hydropower and cooling water), navigation, drinking water and recreation (Van Loon, 2015). Droughts are different to other weather hazards in that they tend to develop slowly, over a large area, with the exact beginning and end often difficult to identify (NHP, 2013). Studying historic droughts is essential to inform water management practises and improve efficiencies in order to build resilience.

The terms droughts, aridity and water scarcity are often confused. Van Loon et al. (2016) define drought as "simply an exceptional lack of water compared to normal conditions" whereas aridity is a climatic feature of a region (low rainfall area) and water scarcity occurs when there is not enough water to meet the demand. Most droughts of the world today have both natural and human drivers (Van Dijk et al., 2013; Van Loon et al., 2016). Artificial influences such as surface and subsurface abstractions, urbanisation and deforestation can all affect the impact of a drought. There are different types of droughts (Wilhite and Glantz, 1985; Alley, 1985; Van Loon, 2015) for example, meteorological (period of below normal rainfall), hydrological (below normal river flow or water level in lakes, reservoirs, groundwater), agricultural (below normal soil moisture levels), and socio-economic (associated with the impacts of the environmental drought types). It is however difficult to define and quantify a drought in absolute terms due to regional and local variations in the extent, duration and intensity of an event.

An array of indices exist to define a drought, broadly separated into two classes (Zargar et al., 2011; Van Loon, 2015;): (i) standardised drought indices; and (ii) thresholds. Commonly used standardised meteorological drought indices are the Standardised Precipitation Index (SPI; Mckee et al., 1993), the Standardised Precipitation and Evaporation Index (SPEI; Vicente-Serrano et al., 2010) and the Standardised Palmer Drought Index (SPDI; Ma et al., 2014). Examples of standardised hydrological indices are the Standardized Streamflow Index (SSI: Vicente-Serrano et al., 2012) and the Standardized Runoff Index (SRI: Shukla & Wood, 2008). An advantage of standardised indices is that regional comparisons can be made because they represent anomalies from a normal situation in a standard way. A disadvantage is that they generally require an appropriate statistical distribution to be identified (unless no extrapolation is required, Vidal et al. 2010). There are similar indices based on spatially continuous remotely sensed data, for example vegetation indices (Aghakouchak et al., 2015; McVicar and Jupp, 1998).

The threshold level method can be used to derive drought characteristics from time series of observed or simulated hydro-meteorological variables. With this method, a period of deficit or drought occurs when the variable of interest (e.g. flow, soil moisture, ground water storage) is below a predefined threshold level (fixed, or variable though the year e.g. seasonal, monthly or daily). A drought event starts when the variable falls below the threshold and continues until the threshold is exceeded again. Characteristics such as drought severity, intensity and duration can then be calculated (Yevjevich, 1967; Hisdal et al., 2004). Advantages of the threshold level method are that there is no need to fit a distribution to the data and that it is easy to calculate the drought characteristics. A disadvantage is that there is no standard definition for the threshold level(s).

One of the main applications of drought indices is drought monitoring and early warning (M&EW). Little can be done to prevent a meteorological drought, however steps can be taken to prevent or alleviate the impact of a hydrological or agricultural drought. Systems such as the U.S. Drought Monitor (droughtmonitor.unl.edu) and the European Drought Observatory (edo.jrc.ec.europa.eu) provide M&EW of droughts. Drought indices can also be used retrospectively to analyse past droughts. In France Vidal et al. (2010) have identified droughts using standardised indices (1958-2008) and in Norway Tallaksen and Hisdal (1997) analyse regional characteristics of drought duration and deficit volume using streamflow data (1931-1990) and the threshold level method.Corzo Perez et al. (2011) provide a global perspective on the spatio-temporal nature of hydrological droughts (1963-2001) using the threshold level method and the WaterGAP Global Hydrology Model. Thanks to flow reconstructions, drought analysis can be carried out even further back in time; Caillouet et al. (2016b), in France, and Meko et al. (2012), in the Colorado basin, make use of reconstructions from Twentieth Century Reanalysis (1871-2012) and dendrochronology (A.D. 762-2005) respectively. See Table 1 in Wada et al. (2013) for more examples of hydrological drought studies using streamflow data.

In this study a national-scale hydrological model, Grid-to-Grid (G2G), is used to examine British droughts from 1891-2015 using the threshold level method. The study objectives are to:

(i) Assess the model performance of the G2G hydrological model at simulating low flows;

(ii) Identify droughts at a national-scale (1891-2015); and
(iii) Analyse drought characteristics in space and time.

These objectives provide the structural sub-headings used in the following Methods, Results and Discussions sections.

2 Study area and materials

Despite Britain's reputation as a rainy country, parts of south-east England in particular are relatively water stressed (Environment Agency, 2008), and it is important to be prepared for drought in order to limit impacts and sustain water supplies (Environment Agency, 2015). Marsh (2007) commented that England and Wales are now considerably more resilient to drought stress than in the nineteenth century when droughts posed a real threat to lives and livelihoods. However, with climate change affecting the water cycle (Watts et al., 2015) and increases in water demand from population growth, it is necessary to continue to build on this resilience. There is no coherent drought-focussed M&EW in the UK (Barker et al., 2016), although the National Hydrological Monitoring Programme assesses the on-going hydrological situation (nrfa.ceh.ac.uk/nhmp) and the UK Hydrological Outlook provides predictions of river flow and groundwater for the next 1 and 3 months (www.hydoutuk.net).

The UK can experience both summer and multi-year droughts. Summer droughts are usually associated with a heat-wave (Yin et al., 2014), and they can be severe but the impacts can be short lived if autumn rainfall levels are healthy (e.g. 2003; Marsh, 2004). Multi-year droughts are often associated with dry winters and springs where aquifer and reservoir stocks are not replenished. These droughts can have long-lasting impacts (e.g. 1988-1992; Marsh et al., 1994). In general, for the wetter parts of northern and western Britain, household and industrial water supply is from surface reservoirs in upland regions (e.g. the Pennines and Wales), and droughts that cause supply difficulties tend to be of shorter duration and due to a dry spring and summer (Jones and Lister, 1998). In the south and east of England, where groundwater is the principle water supply, problems only tend to occur when flows have been low for at least 15 months (Jones and Lister, 1998) and where groundwater recharge has been minimal.

Direct drought impacts of relevance to the UK include: reduction/loss of agricultural production, reduction of water supply, reduction of energy supply, and environmental impacts such as algal blooms, wildfires, loss of habitats, and river and lake pollution (NHP, 2013). Indirect drought impacts (i.e. those associated with droughts happening elsewhere) include droughts in food producing regions driving higher food prices. The actual impact depends on preparedness and vulnerability to drought and risk reduction during a drought. The impacts of droughts are typically poorly documented, although initiatives such as the European Drought Impact Report Inventory (www.geo.uio.no/edc/droughtdb) and the Chronology of British Hydrological Events (CBHE; cbhe.hydrology.org.uk) provide searchable databases of text records of historical events.

Compared to flood research, drought research in the UK has been relatively neglected, although recent studies have looked at standardised drought indicators (Barker et al., 2016), drought termination (Parry et al., 2016), multi-annual droughts in the English Lowlands (Folland et al., 2015) and implications of historic droughts on water supply yield calculations (Lennard et al., 2015).

2.1 Hydrological model

The Grid-to-Grid (G2G) is a national-scale runoff-production and routing model that provides estimates of river flows, runoff and soil moisture on a 1km^2 grid across Great Britain (Bell et al., 2009). The model has a time step of 15 minutes and is used within the Flood Forecasting Centre (England and Wales) and the Scottish Flood Forecasting Service for countrywide operational forecasting (Price et al., 2012; Maxey et al., 2012). The G2G has also been used to assess the impact of climate change on flooding (Bell et al., 2012; Bell et al., 2016). An advantage of G2G is that it has one spatially consistent configuration for the whole model domain, and is able to represent a wide range of hydrological regimes due to use of present day spatial datasets of soil, digital terrain and land cover in the model construction. The river flow estimates produced by the model are natural flows and do not take into account surface or groundwater abstractions. Work on enhancing the model to account for abstractions is underway, but not reported here.

The G2G requires as input gridded time series of precipitation and potential evaporation (PE). For the analyses undertaken here, two model simulations have been produced, one for low flow model performance assessment (1971-2000) and one for historic drought identification and characterisation (1891-2015) (Figure 1). Both model runs use 1km^2 daily precipitation from CEH Gridded Estimates of Areal Rainfall (CEH-GEAR; Tanguy, et al., 2015; Keller et al., 2015), which is based on measurements from a national network of rain gauges (see Figs. 2 and 3 of Keller et al., (2015) for the number, and spatial distribution, of rain gauges) and is available for 1890-2015. Periods in the first half of the 20th century for which rainfall measurements were particularly sparse and identified as missing in the CEH-GEAR datasets (see Fig. 6 of Keller et al., 2015) were infilled. The two nearest available recording rain gauges were combined using inverse distance weighting and scaling by monthly average rainfall patterns. This infilling resulted in a complete rainfall record with no gaps allowing for a continuous G2G model run from 1891 to 2015. The 1971-2000 performance assessment uses 40kmx40km gridded monthly estimates of short grass PE from the Met Office Rainfall and Evaporation Calculation System (MORECS; Hough and Jones, 1997). This Penman-Monteith PE was previously used for model calibration (Bell et al., 2009) and is therefore the most appropriate for assessing model performance for low flows. However, MORECS PE is not available pre-1960 so the historic drought analysis used a temperature-based method (Oudin et al., 2005) to estimate monthly PE from gridded (5kmx5km) monthly temperature observations available from 1891 (Perry and Hollis, 2005). Oudin et al., (2005) PE is unable to incorporate the meteorological influences such as wind and humidity that are included in MORECS, so to correct for regional differences a set of monthly spatial correction factors (Crooks and Kay, 2015) was applied. These grids of correction factors were derived by comparing long-term mean monthly values of Oudin PE (1961-1990) to those from MORECS (smoothed to 5km). For use in G2G, the 5kmx5km PE data were copied to each of the corresponding 25 1km^2 grid boxes of the hydrological model grid and then divided equally over each time step. The 1km^2 daily precipitation was divided equally over each time step. To allow for a model spin-up of 2 years prior to 1891, a rainfall grid for 1889 was created using data from the 53 available rain gauges in that year (in a similar way to that used for CEH-GEAR, available from 1890), and the PE for 1891 was copied to 1889 and 1890. This provided sufficient inputs for model spin-up for 1889-1890, with a realistic water balance (Supplementary Figure 1 illustrates that a 2-year spin-up period is sufficient); the drought identification and characterisation was then carried out for 1891-2015.

2.2 Historic observed droughts

Information on historic observed droughts is needed to assess the ability of national-scale models such as G2G to identify historic droughts. Drought has been a recurring feature of the British climate, but many events predate the widespread availability of observed river flow and groundwater time series. Cole and Marsh (2006) and Marsh et al., (2007) use a range of hydro-meteorological data, impact information (from the CBHE) and hydrological judgement, rather than a single hydro-meteorological index, to identify 'major' and 'moderate' droughts in England and Wales (see Table 1 and 'observed droughts' line in Figure 7 and Figure 8). Droughts were identified as 'major' on the basis of ranked runoff deficiencies (over 9-24 month periods), supported by other evidence such as long time series of river flows (gauged and extended) and groundwater levels (Marsh et al., 2007). Droughts also had to impact over a wide geographic area to be classed as 'major'. The approach taken by Cole and Marsh (2006) and Marsh et al. (2007) does not allow quantitative thresholds to be established to distinguish categories of drought severity; correspondingly the distinction between 'major' and other severe events may not always be clear-cut. More recent droughts not included in the analysis by Cole and Marsh (2006) are 2004-2006 (Marsh et al., 2014) and 2010-2012 (Kendon et al., 2013), and for these a severity category has not yet been assigned. There is little information about observed Scottish droughts and a classification of major and moderate has not been made (Gosling et al., 2012). It is important to note that Cole and Marsh (2006) do not distinguish between meteorological or hydrological drought events, however the report provides a consistent source of information on the dates and approximate severity of historic droughts for comparison with those identified through model simulation. Documentary evidence of drought is patchy and tends to decline the further back in the historical record one goes, which gives a false impression of drought incidence, however any information is still essential for assessment of historical droughts.

Along with the information on droughts in England and Wales, Cole and Marsh (2006) also provide specific regional information for droughts occurring in East Anglia and North West England. Appendix 1 of the report is a table of drought episodes providing additional information (on primarily river flows and groundwater levels) for the regions of East Anglia and North West England. This additional information allowed a more focussed quantitative assessment of the hydrological model's ability to identify droughts in these two regions. Note that there is little information on the impacts of droughts in 1939-1945 due to limited recording during the Second World War.

3 Methodology

3.1 Hydrological model performance for low flows

Model performance for daily and monthly mean low flows was assessed at 61 locations by comparing with gauged daily river flow data obtained from the National River Flow Archive (nrfa.ceh.ac.uk). Figure 2a shows the locations of the gauging stations and their catchment boundaries, and Supplementary Table 1 lists the stations and some of their catchment properties. The 61 catchments represent a diverse range of catchment characteristics in terms of topography, geology, land use and climate. Among the 61 catchments, 39 are part of a network of Benchmark catchments (Bradford and Marsh, 2003) where the gauges are considered to have good hydrometric performance (reliable data i.e. good ratings and no problems with the stilling well), a relatively long record with near-natural regimes (relatively undisturbed) and be representative of regions across the UK. 1971-2000 was selected for the model performance assessment to maximise data availability (see Supplementary Figure 2) and because it is a commonly used baseline in meteorology and hydrology. Observed river flow series are not 100% complete, and therefore there are some periods with missing data, these were excluded from the analysis. As with the drought analysis, there was a spin-up period (model run initialised in 1960) before the assessment period. For the Thames at Kingston, where both naturalised and gauged daily flows are available, the naturalised flows were used. The G2G grid-cell corresponding to each gauged location was identified, and the agreement between the observed and simulated river flows was quantified (Section 4.1).

Two performance scores were used to quantify different aspects of the agreement between simulated and observed flows; a score based on temporal series and a score based on the flow duration curve (FDC). The time series performance score is based on the model efficiency criterion of Nash and Sutcliffe (1970) but adapted for use with low flows through the use of logarithms. Specifically, the efficiency score is defined as

$$NSE\log = 1 - \frac{\sum(\ln(Q_t + \varepsilon) - \ln(M_t + \varepsilon))^2}{\sum(\ln(Q_t + \varepsilon) - \overline{\ln(Q_t + \varepsilon)})^2} \qquad \varepsilon = \frac{\overline{Q_t}}{100},$$

where Q_t are the observed flows (m^3s^{-1}), M_t are the modelled flows (m^3s^{-1}), ε is a small value (usually taken to be the observed mean flow divided by 100) and *t* is the time (day or month). An NSElog value of 1 indicates a perfect fit, whilst a negative value indicates that the fit is worse than the mean.

The FDC performance score, the percentage bias in low flow volume (LFV), compares the statistical characteristics of the flows rather than the time-step equivalence. It is calculated from the low flow end of the FDC, which is obtained by ranking the flows from a (daily or monthly) time series and selecting the flow Q_p corresponding to the percentile point *p* (between 1 and 100); Q_p is thus the flow equalled or exceeded *p%* of the time. Following Kay et al. (2015),

$$LFV = 100 \frac{\sum_{p=70}^{95}\left[f(M_p) - f(Q_p)\right]}{\sum_{p=70}^{95} f(Q_p)},$$

where the function *f* is taken as the square root, and *Q* and *M* are the observed and modelled flows respectively. LFV only compares up to the 95th percentile flow (from the 70th) so as not to include extreme low flow values, which can be more severely affected by abstractions, effluent returns etc. A positive LFV value indicates that the modelled flow is generally greater than observed flow.

3.2 Drought identification (1891-2015)

Droughts are identified using the threshold level method (Yevjevich, 1967; Hisdal et al., 2004; Fleig et al., 2006). The method is applied to gridded time series of simulated monthly mean river flow and soil moisture to identify historic droughts, and their characteristics, across Great Britain. Although many applications of the threshold level method have been applied to daily flow data (Tallaksen et al., 1997; Fleig et al., 2006; Corzo Perez et al., 2011; Van Loon and Laaha, 2015) there are several studies that have used monthly series (Mohan and Rangacharya, 1991; Hisdal and Tallaksen, 2003; Tallaksen et al., 2006; Sharma and Panu, 2008; Van Huijgevoort et al., 2012). Monthly time series are used here, rather than daily, as the typical time scale of droughts is monthly to yearly and using monthly data reduces potential issues with the dependency of events (Rangecroft et al., 2016) and makes the analysis, covering 125 years, more manageable.

The general threshold level method compares a time series of variable X to a threshold X_{thresh} (fixed or varying). A drought event starts when the variable falls below the threshold and continues until the threshold is exceeded again. However, there is no standard way of defining X_{thresh}. In this study a variable threshold is used, the long-term mean for each month X_{mon} (1971-2000), this has the effect of removing the seasonality from the time series. In order to compare drought characteristics for different catchments the time series of anomalies $X - X_{mon}$ are standardised (Peters et al., 2003) by dividing by the long-term mean standard deviation for each month σ_{mon}. A "drought" is then defined as a period of time for which X is below normal (or $X - X_{mon} < 0$), i.e. as a deficit or difference from the long-term mean. The characteristics of a drought are then;

(i) standardised drought intensity — the deviation of $(X - X_{mon})/\sigma_{mon}$ below zero;
(ii) drought duration — the length of time below zero; and
(iii) standardised drought severity — duration multiplied by mean standardised intensity.

The advantage of standardising is that different regions over the entire country can be compared, the disadvantage is that it is not possible to go back to a volume if you want to study a specific region.

To identify particular drought years and enable annual mapping, the most severe simulated drought in each year is selected and national grids of drought characteristics (standardised severity, standardised maximum intensity and duration) are made. The drought identification algorithm accounts for multi-year droughts by keeping track of deficits in each year of a multi-year event. At the end of each year of the multi-year event the cumulative duration and severity and the maximum intensity (over the event) is attributed to that year. Therefore the year in which the drought ends has the characteristics of the whole multi-year event. See Supplementary Section 2.2 for a more detailed description of the method and an example.

To compare annual drought occurrence and severity to the historic observed droughts (Section 2.2), severity thresholds have been identified to classify the simulated droughts as major or moderate (Supplementary Figure 3). The annual 1kmx1km grids of standardised drought severity are averaged over 19 river-basin regions (a division of the UK land area based on the Water Framework Directive River Basin Districts, Figure 2b), and if the average severity for a region is above the major (moderate) threshold then the region is deemed to be experiencing a major (moderate) drought in that year. The thresholds have been manually tuned so that the analysis of simulated flows and soil moisture identifies a good proportion of the observed drought years in 1891-2003, without identifying too many additional years as droughts. Thresholds are defined separately for river flow and soil moisture drought severity (river flow: major 8, moderate 4; soil moisture: major 16, moderate 8), although the observed droughts have a greater emphasis on hydrological and meteorological rather than agricultural droughts.

A quantitative assessment of the skill in the above drought identification procedure has been undertaken for East Anglia and North West England (1920-2003) for which local information on drought was available (Appendix 1 of Cole and Marsh, 2006). This assessment used skill scores comprising: probability of detection (*POD*), false alarm ratio (*FAR*) and critical success index (*CSI*) (Schaefer, 1990). Specifically, if *h* is the number of droughts that are both observed and modelled (hits), and *m* is the number of observed droughts that are not modelled as droughts (misses), then

POD = h/(h+m). If *f* is the number of droughts that are modelled but not observed (false alarms) then *FAR = f/(h+f)*. Both POD and FAR range from 0 to 1; a good score would be a high *POD* and low *FAR* (i.e. high level of detection, few false alarms). Then *CSI = h/(h+f+m),* taking into account hits, misses and false alarms to give a more balanced score, again ranging from 0 to 1 with 1 indicating a perfect prediction. Cole and Marsh (2006) state that judgement needs to be exercised in assigning 'major drought status' to events prior to 1920 in particular, due to variations in the quality and completeness of the hydro-meteorological evidence, thus the quantitative assessment is restricted to 1920-2003.

The drought identification results are presented in Sections 4.2.1 (national) and 4.2.2 (regional). It should be noted that the severity threshold selection is somewhat subjective, as is the major and moderate classification for historic observed droughts (Section 2.2), and this needs to be borne in mind when interpreting the results.

3.3 Analysis of drought characteristics in space and time

The paucity of observed river flow and groundwater time series pre-1950 means that there is a danger that available observed data could be unrepresentative of the full historical series (Cole and Marsh, 2006). Hydrological model simulations driven by more readily-available meteorological data thus provide an opportunity to investigate the temporal and spatial nature of British droughts with greater consistency.

To examine the spatial and temporal nature of (river flow and soil moisture) drought characteristics through the 20th century, for each pixel on the 1kmx1km grid the standardised severity, standardised maximum intensity and duration of all simulated droughts (longer than 1 month in duration) were averaged over four time-slices (1891-1920, 1921-1950, 1951-1980 and 1981-2010). These temporal averages were then summarised for each of the 19 river-basin regions (Figure 2b) by presenting box and whisker plots showing the range of values within each region for each time-slice (Section 4.2.3). Note that this analysis used all simulated droughts (except those of only 1 month duration), rather than only the most severe drought in each year (used for the drought identification, Section 3.2). Droughts of only 1 month duration were excluded so as not to include a potentially large number of very short, and therefore likely insignificant, events that could skew the statistics.

4 Results

4.1 Hydrological model performance for low flows

Figure 3 shows the spatial distribution of NSElog and the percentage bias in the low flow volume (LFV) for both daily and monthly mean river flows. For NSElog (Figure 3a) there is lots of variability between the catchments, with some having very good performance [e.g. Taw, Naver and Dyfi] and others poor performance [e.g. Dove, Mimram and Itchen]. Generally there is better performance for low flows on the monthly time scale compared to the daily scale. The majority of the catchments assessed have reasonable performance, with 28 catchments (46%) having NSElog ≥ 0.7 at the daily time scale and 42 (69%) at the monthly time scale. For completeness the NSE and NSE with the square root of flow are included in Supplementary Figure 4, which shows that generally the values are a little higher than for NSElog (Figure 3) suggesting better performance across the whole flow range. Supplementary Figure 5 shows that the results from the two runs using different PE (Figure 1) are comparable. This gives confidence in the run used for the drought identification study where PE was calculated from temperature grids.

For the daily time scale there are 35 catchments (57%) with LFV in the range -20 to +20%; 48 (79%) at the monthly time scale (Figure 3b). Again, the model is better at simulating low flows on the monthly time scale compared to the daily scale. The spatial variability in performance can also be seen, with some catchments having good performance [e.g. Naver and Dyfi] and others poorer performance [e.g. Beult and Stringside]. At the monthly time scale there are 7 catchments with a negative bias (red) and 6 with a positive bias (blue). The catchments with a positive bias tend to be relatively small catchments in the southeast of England, while those with a negative bias are scattered throughout Britain.

Figure 4 shows simulated and observed hydrographs of monthly mean river flow and flow duration curves (calculated from monthly flow time series for 1971-2000) for two catchments. They were selected as examples where the model simulation matches well with the observed (Taw at Umberleigh) and less well (Warleggan at Trengoffe). For the low flow part of the hydrograph, the simulated flows for the Warleggan are generally too low compared to the observed flows, leading to a flow duration curve that is underestimated. By contrast, flows simulated for the Taw better match the observed flows.

A comparison between model performance and catchment characteristics (catchment area, average rainfall, base flow index, soil type and altitude) found no clear relationships (not shown). This suggests that G2G's use of spatial datasets is generally successful in enabling the model to allow for differences in hydrological response due to different physical characteristics (although future developments in the availability and resolution of digital datasets may allow further improvements). The fact that the model performs reasonably well in simulating low flows for a range of catchments across Britain, especially at the monthly time scale, suggests that it can be reliably used for national-scale modelling of droughts.

4.2 Drought identification (1891-2015)

4.2.1 National assessment

Figure 5 shows annual maps of the standardised drought severity for river flow for 1891-2015 (equivalent maps for soil moisture in Figure 6). Observed drought years have borders (major – red, moderate – orange, more recent (unclassified) – brown). The years with highest standardised drought severity correspond well to the years with borders.

Years which particularly stand out in Figure 5 and Figure 6 include 1921-1922, 1934, 1944 and 1976 (southern Britain) and 1929, which appears to have affected the whole of Britain. Figure 5 and Figure 6 also highlight multi-year persistence of droughts in groundwater-dependent areas in the southeast (e.g. 1935, 1945-46, 1977 and 1998). There is often high simulated drought severity in north-west Scotland when there are not severe droughts elsewhere (e.g. 1916, 1920, 1936, 1940, 1969, 1977 and 2002).

Figure 7 shows the drought years identified using the model simulation separated into 19 regions, classified as major or moderate using severity thresholds (Section 3.2). The top line shows observed droughts (Section 2.2), then the `Eng & Wales' line summarises years where one or more of the separate regions in England and Wales (see Supplementary Table 3) has been identified by the model as being in (major or moderate) drought. A similar summary line is provided for modelled droughts in Scotland, although there is little information about observed Scottish droughts.

Overall, the droughts picked out by the identification method and G2G model output compare reasonably well to the known historic droughts. Some of the more severe droughts have been identified correctly (e.g. 1921-1922, 1976) and moderate droughts like 1989 and 2003 are also identified correctly. The subjective nature of the observed drought series means that only a loose comparison can be made between the modelled and observed droughts, but the results are encouraging. The south east England droughts that stood out in Figure 5 are also apparent in Figure 7 (1921-1922, 1934, 1944 and 1976) and can be seen in both river flow (Figure 7a) and soil moisture (Figure 7b). In the late 1940s the droughts in England tended to persist for a few years in both the river flow and soil moisture (Figure 7a, b). Soil moisture droughts often start later and/or finish later compared to corresponding flow droughts (Figure 7c). According to the model simulation the river flow drought in 1929 affects all regions, whereas soil moisture was not so widely affected. In 1972 and 1973 soil moisture droughts are identified in some parts of Scotland, however without much evidence of observed Scottish droughts it is difficult to determine whether these really were droughts. However Figure 7 suggests that Scotland is subject to frequent moderate droughts (particularly in terms of river flow) but a lower incidence of major droughts than E&W.

4.2.2 Regional assessment

Figure 8 shows the comparison of observed droughts for East Anglia and North West England against those identified from the simulated monthly mean flows using the threshold level method (classified as major or moderate using severity thresholds). Using the detailed information on historic observed droughts in East Anglia and North West England (Section 2.2) it is possible to assess the drought identification method using skill scores; POD, FAR and CSI (Section 3.2).

For East Anglia (Figure 8a), the method identifies 76% (POD, 0.76) of the known (major and moderate) historic droughts with a low FAR (0.12), and a good CSI (0.69). The method has missed one major drought year (1995) and 6 moderate drought years, but 66 out of 84 years (79%) were correctly classified. There were more years where drought status was underestimated (i.e. no drought simulated but drought observed, or only moderate drought simulated but major drought observed; 15) than overestimated (i.e. drought simulated but no drought observed, or major drought simulated but only moderate drought observed; 3). For North West England (Figure 8b), the method picks up 48% of the known historic droughts, with a low FAR (0.06) and a relatively good CSI (0.47). The method has missed two major drought years (1976 and 1997) and 14 moderate drought years, but 63 out of 84 years (75%) were correctly classified. Again more years were underestimated (20) than overestimated (1). The extent to which this comparison is affected by the subjectivity of the major and moderate classification for historic observed droughts (Section 2.2), and the selection of the severity threshold (Section 3.2), is unclear.

4.3 Analysis of drought characteristics in space and time

The boxplots in Figure 9 summarise the ranges of standardised severity, standardised maximum intensity and duration of river flow droughts for each of the 19 regions, averaged over four time-slices (Section 3.3). Some regions (e.g. Thames, Anglian and SE England) tend to have more severe droughts and a greater range of average drought severity across the region (Figure 9a). These regions also tend to have longer duration droughts, and a greater range of average durations across the region (Figure 9c), but they possibly tend to have lower intensity droughts (Figure 9b). The maps in Figure 10a-c show that these regional variations are due to the presence of significant areas of groundwater within these regions, as the locations with higher severity and duration values coincide with the locations of main aquifers, especially the chalk (see Figure 1 p179, CEH and BGS, 2008). Figure 9c shows that durations of up to 19 months are simulated for droughts in the Thames region (1921-1950) and the Severn region (1891-1920) and 17 months in Thames and Anglian (1981-2010). The simulations suggest that on average, across the regions, historic droughts tend to be between 3 and 6 months duration, although groundwater-dependent regions can experience much longer droughts. Figure 10d shows the number of major droughts (severity ≥ 8) for 1891-2015, highlighting the variation across Great Britain.

In some regions the median severity has been decreasing between time-slices (e.g. Severn and W Wales) (Figure 9a). In most of the Scottish regions (N Highlands, NE Scotland, Tay, Tweed, Solway, Clyde, Argyll and W Highlands) 1951-1980 had the highest median severity. The regions with decreasing severity over time have also had decreasing intensities (Figure 9c) over the later three time-slices. For the Tweed and Solway regions the pattern of 1951-1980 having the highest severity is reflected in the intensity however there are also regions where the intensities have decreased over the time-slices after 1920 (e.g. N Highlands, Tay and Argyll). For the Thames and SE England regions 1921-1950 was more severe on average, with a wider range of values across the region. 1951-1980 was the least severe, with duration and severity showing a similar pattern but intensity increasing and then decreasing between the three time-slices. Figure 9b shows that the majority of the regional medians of drought maximum intensity have increased from 1891-1920 to 1921-1950 and then decreased between successive time-slices.

The equivalent boxplots for soil moisture drought characteristics (Figure 11) show a much greater range of values than the characteristics for river flow droughts, although the medians are similar. The soil moisture droughts can be more severe than river flow droughts, and can last even longer (up to ~45 months). The Anglian, SW England, Severn, W Wales and Dee regions show a decrease in the median severity over the successive time-slices after 1891-1920.

Had the analysis used only the period for which river flow observations are more plentiful (mostly post-1960) it might have concluded that, in the Thames and SE England regions for example, droughts have been getting more severe over time (green and blue boxes in Figure 9a). However, by including the model simulation for 1891-1920 and 1921-1950 (cyan and red boxes) it becomes evident that the medians fluctuate across the time-slices and that there were more severe droughts in the earlier part of the 20th century, thus the patterns of change in drought characteristics might be due to natural variability in the climate system, rather than any systematic change due to climate change.

5 Discussion

5.1 Hydrological model performance for low flows

Unlike for floods, where daily or sub-daily peak river flows are important, droughts tend to develop over months and therefore reliably simulating monthly mean river flows is arguably more important than daily time-scales. Analysis undertaken here showed that G2G generally simulates low monthly flows well (Section 4.1).

Previous high flow studies have shown that G2G simulation performance is less successful for low relief and/or groundwater-dependent areas (Bell et al., 2009); the Mimram and the Itchen are examples of groundwater-dependent catchments. It was found that catchments with a positive LFV bias tend to be relatively small catchments in the southeast of England, while those with a negative bias are scattered throughout Britain. Smaller catchments are more likely to have errors in catchment delineation (from use of a 1km gridded landscape representation), potentially leading to errors in water balance, and those in the drier south-east are typically subject to substantial abstraction (especially if groundwater-dependent), so the natural flows simulated by G2G are more likely to be an overestimate, leading to a positive LFV bias. One reason why the G2G may simulate the Warleggan less well (Figure 4) is because of the unusually large baseflow component (BFI 0.71) for a small ($25km^2$) upland catchment, arising from storage and passage of water through kaolinised granite. It is likely that the unusual storage and geology is not well represented by the soil data used by G2G, which has only 29 classes (Boorman et al., 1995).

When assessing the agreement between a model simulation and observations it is important to keep in mind the uncertainties associated with both. Models are imperfect in their nature due to underlying assumptions, model structure and configuration. In particular, the G2G provides estimates of natural, not gauged, flows. UK rivers can be subject to flow regulation (e.g. reservoir operation, compensation flows) in addition to factors such as abstractions and discharges that are likely to be influential on low flows. If sufficient information on these artificial influences could be obtained and included in the model then a closer comparison with observations could be possible. Ongoing work aims to enhance G2G for low flows by introducing anthropogenic influences on flows, such as surface/groundwater abstractions and discharges. Uncertainties also arise from the input data used to drive the hydrological model; there are errors in measuring precipitation (rain and snow), and there are a multitude of methods for estimating potential evaporation (Kay et al., 2013). Flow observations are also imperfect due to a number of factors; Coxon et al. (2015) separate these factors into data (e.g. calculating cross-sectional area for rating curves, inadequate temporal or spatial sampling), natural (changes of the river section over time), rating curve (e.g. extrapolation) and human (e.g. change of location).

Soil moisture simulations have not been compared with observations because a consistent dataset of soil moisture observations is not currently available. This is likely to change with on-going work digitising soil moisture data and a comparison will follow in the future.

5.2 Drought identification (1891-2015)

The G2G model simulation with the threshold level method can be used to identify historic droughts (Section 4.2), although the comparison with historic observed droughts is limited by the lack of a more comprehensive review of historic droughts and their relative severity. The primary reference used here, Cole and Marsh (2006), does not include Scotland, or distinguish between meteorological and hydrological droughts which also complicates a national-scale hydrological comparison. However, the regional assessment for East Anglia and North West England indicated a probability of detection of 0.76 and 0.48 respectively, reflecting reasonable skill in drought identification. To facilitate drought identification at the national scale, national thresholds (for major and moderate droughts) were chosen for the whole of Britain. This enabled a nationally consistent approach, but the regions are hydrologically different and thus vulnerable to different types of drought with varying impacts. There is currently insufficient spatial information on historic droughts to identify regional thresholds.

It was shown (Figure 5) that years with higher standardised drought severity in England correspond well to years of known droughts. There is often higher drought severity in the north-west of Scotland, which could be due to poor quality rainfall observations (either gauge coverage or unrepresentative gauges) in this region, especially in the early part of the time period. The limited knowledge of historic Scottish droughts constrains the ability to compare model simulations and observations, but simulation in upland areas of Scotland could be improved if a snow module was applied with G2G (as in Bell et al. 2016). However, the limited availability of historical daily minimum and maximum temperature data meant that a snow module could not be applied prior to 1960. Kay (2016) notes that snow can have a significant effect on river flows in some parts of Scotland, enhancing flows in spring and into summer (during snowmelt), with lower summer flows occurring in years with less snow cover. In the late 19th and early 20th century, when average temperatures were lower and thus there was more snow, this seasonal flow pattern is likely to have been more prevalent in other parts of Britain too. One possibility is to supplement observed data with re-analysis data like that from 20CR (Compo et al. 2011), available at a 2° resolution for 1871-present, using some form of downscaling (Caillouet et al. 2016a).

The limited availability of historical meteorological data also necessitated the use of a PE scheme based on monthly temperature data for the 1891-2015 model run, rather than the more commonly used but data intensive Penman-Monteith PE scheme (Monteith, 1965), so the effect of potential changes in other variables (e.g. wind) over time is not included in the PE estimates (McVicar et al., 2012; Kay et al., 2013). Also not included is the effect that potential changes in stomatal conductance can have on PE (Rudd and Kay, 2016).

5.3 Analysis of drought characteristics in space and time

The analysis of drought characteristics (Section 4.3) showed there is substantial spatial and temporal variability, but no consistent changes through time. This result agrees with Hannaford (2015), who report that observation-based analyses of low flows and droughts have found no compelling evidence of any long-term trends of increased drought severity in England and Wales and that natural variability is the dominant factor. Similarly, Sheffield et al. (2012) find little change in meteorological drought globally over 1950-2010, although this is the subject of debate as there have been a number of studies producing apparently conflicting results (Trenberth et al. 2014).

The analysis also showed that groundwater-dependent regions can experience longer and more severe droughts, similar to Tallaksen et al. (2009), and that soil moisture droughts can be more severe and last longer than river flow droughts. This result is similar to that of Vidal et al. (2010) , who showed that in France agricultural (soil moisture) droughts tend to last longer than meteorological droughts.

Further analysis would ideally test the robustness of the results to selection of alternative thresholds in the threshold level method. Different thresholds would give different characteristics (e.g. a stricter threshold would by definition give fewer droughts, of shorter duration, lower intensity and lesser severity), but the relationship between the characteristics would be unlikely to change (Oosterwijk et al., 2009; Van Loon and Van Lanen, 2012). There are however lots of studies using a range of different thresholds, and the approach by Weiß et al. (2007) is particularly interesting as it combines the long-term monthly mean threshold (as applied here) with a fixed threshold in order to limit the accounting of deficits during the wetter part of the year. Caillouet et al. (2016b) similarly apply a mixed threshold.

6 Conclusions

This study is the first to use a national-scale gridded hydrological model to investigate droughts across Great Britain over the last century. It is shown that the model can simulate low flows well in many catchments across the country, and that the gridded model output can be used with the threshold level method to identify historic drought years. An assessment of drought characteristics shows substantial spatial and temporal variability, but no consistent changes through time. The simulations performed here particularly help the analysis of early droughts.

Van Lanen et al., (2016) argue that a hydrological, rather than purely meteorological, perspective on droughts, as provided here, is critical, as many drought impacts are related to the hydrology rather than solely the weather, and the characteristics of meteorological and hydrological droughts can be very different. However, when examining drought in a historical context it is also important to be aware of possible changes in climatic variability over the historical record (Folland et al., 2002), the changing ability of a region to cope with drought (Wanders et al., 2015), and the decrease in documentary evidence the further back in time (Cole and Marsh, 2006).

Future work will use ensembles of baseline and future climate simulations, produced using Weather at Home (www.climateprediction.net/weatherathome/), to investigate how river flow and soil moisture drought occurrence and characteristics may change in the future, under climate change (Prudhomme et al., 2014). This hydrological analysis could help inform long-term planning for drought management.

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Figure captions

Figure 1: Flow diagram of the G2G hydrological model runs. Inputs in grey and outputs in black.

Figure 2: a) Locations of the 61 catchments used in the model performance assessment. Benchmark catchments are outlined in black. The circles mark the gauging station (catchment outlet). b) The 19 river-basin regions used in the drought identification and characterisation.

Figure 3: Spatial distribution of NSElog (a and b) and the percentage bias in low flow volume LFV (c and d) using daily (left) and monthly (right) time series for the 61 catchments (1971-2000).

Figure 4: Observed monthly mean river flow time series (black) compared to simulated (red) for two example catchments; the Taw at Umberleigh (a) and the Warleggan at Trengoffe (d). Flow duration curves (monthly mean flow) for the two catchments (b and c).

Figure 5: Standardised drought severity for river flow (1891-2015). Observed drought years have a border (major – red, moderate – orange, more recent (unclassified) – brown).

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Figure 7: Standardised drought severity for a) river flow and b) soil moisture and c) both flow and soil moisture. In c) major and moderate droughts have been considered together.

Figure 8: Observed droughts and simulated river flow droughts for a) East Anglia and b) North West England.

Figure 9: River flow drought characteristics, a) standardised severity, b) standardised maximum intensity and c) duration, for 19 river-basin regions, averaged over four time-slices; 1891-1920 (cyan), 1921-1950 (red), 1951-1980 (green) and 1981-2010 (blue). The boxes show the interquartile range for each region, with the median shown by the thicker line within each box. The whiskers mark the 5^{th} and 95^{th} percentiles, and the dashes outside the whiskers show the minimum and maximum values.

Figure 10: Maps of average river flow a) standardised severity, b) standardised maximum intensity and c) duration for 1981-2010. d) number of major droughts (severity ≥ 8) for 1891-2015. A threshold catchment area of $25km^2$ has been used to show the main rivers more clearly.

Figure 11: Soil moisture drought characteristics, a) standardised severity, b) standardised maximum intensity and c) duration, for 19 river-basin regions, averaged over four time-slices; 1891-1920 (cyan), 1921-1950 (red), 1951-1980 (green) and 1981-2010 (blue). Boxes and whiskers as in Figure 9.

Table captions

Table 1: Historic droughts of England and Wales and the regions of East Anglia and North West England, as identified by Cole and Marsh (2006).

National-scale analysis of simulated hydrological droughts (1891-2015)

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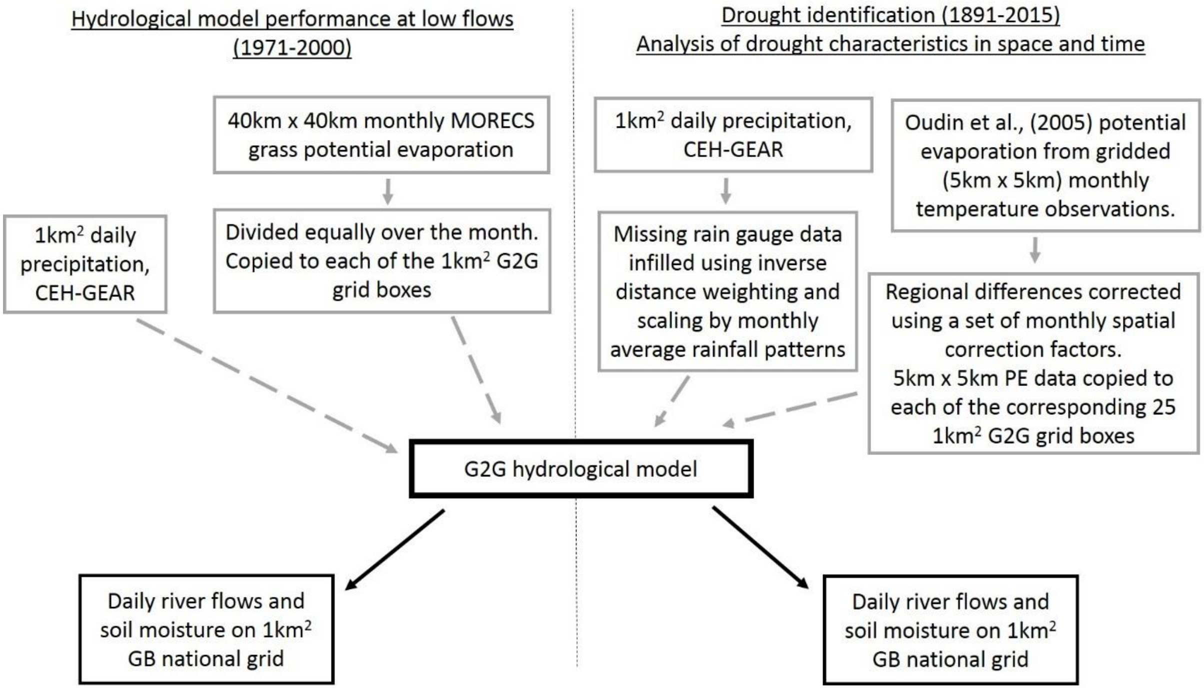

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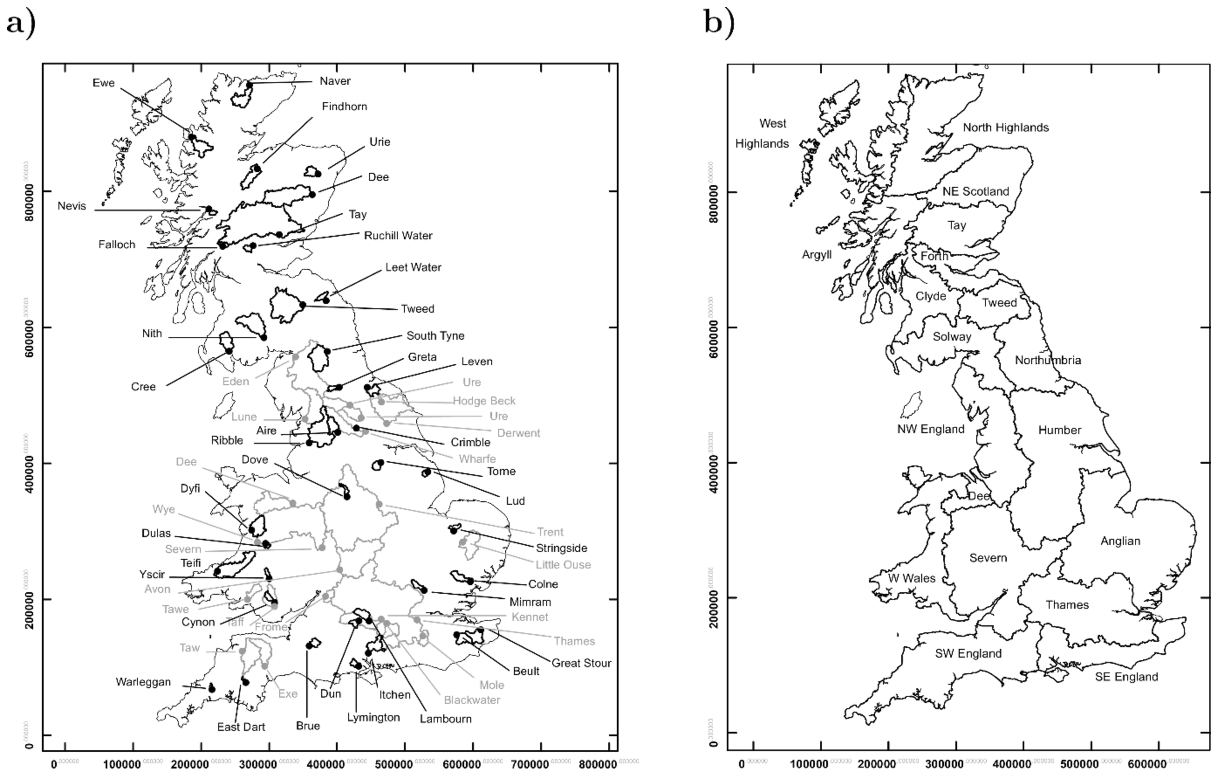

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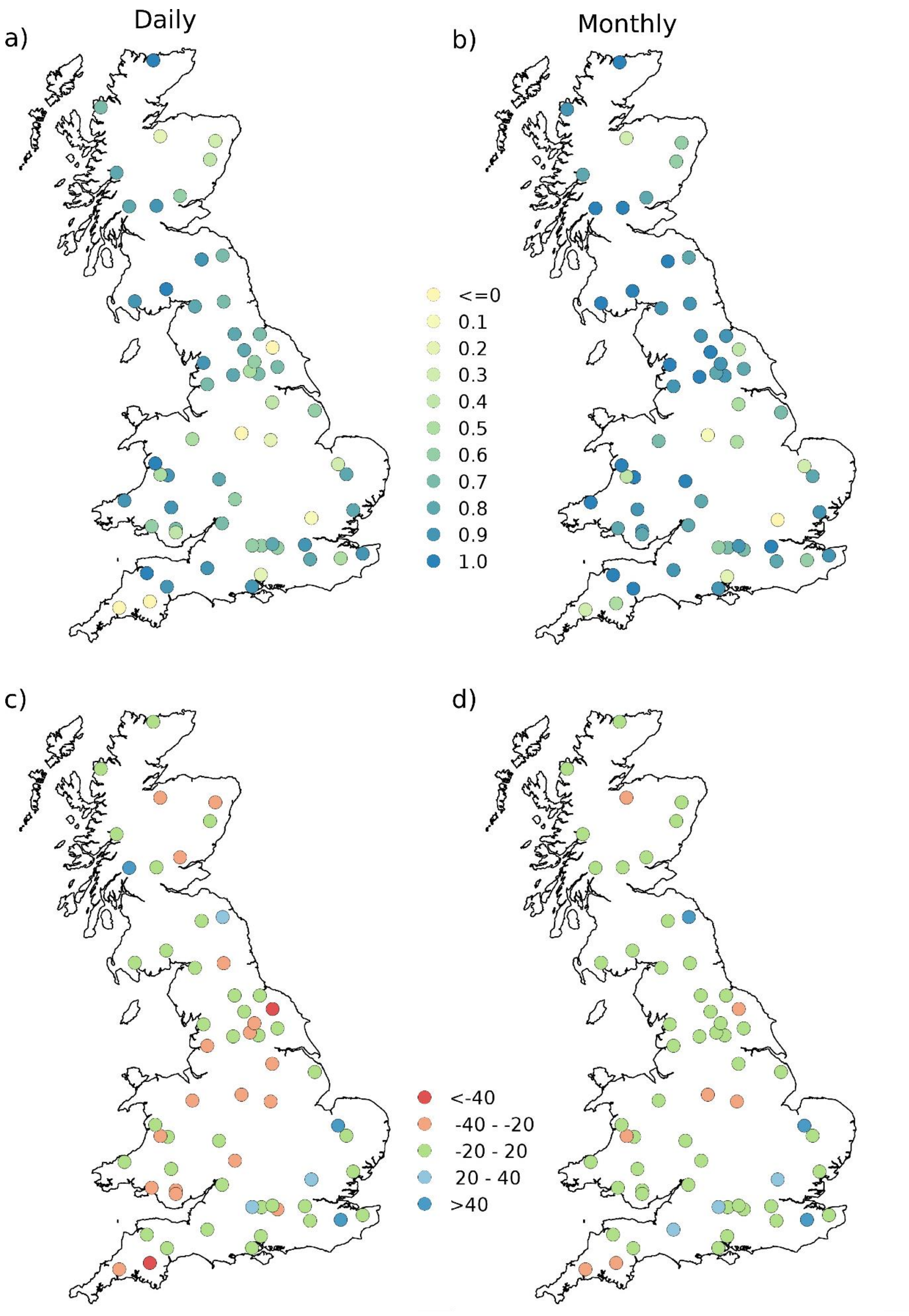

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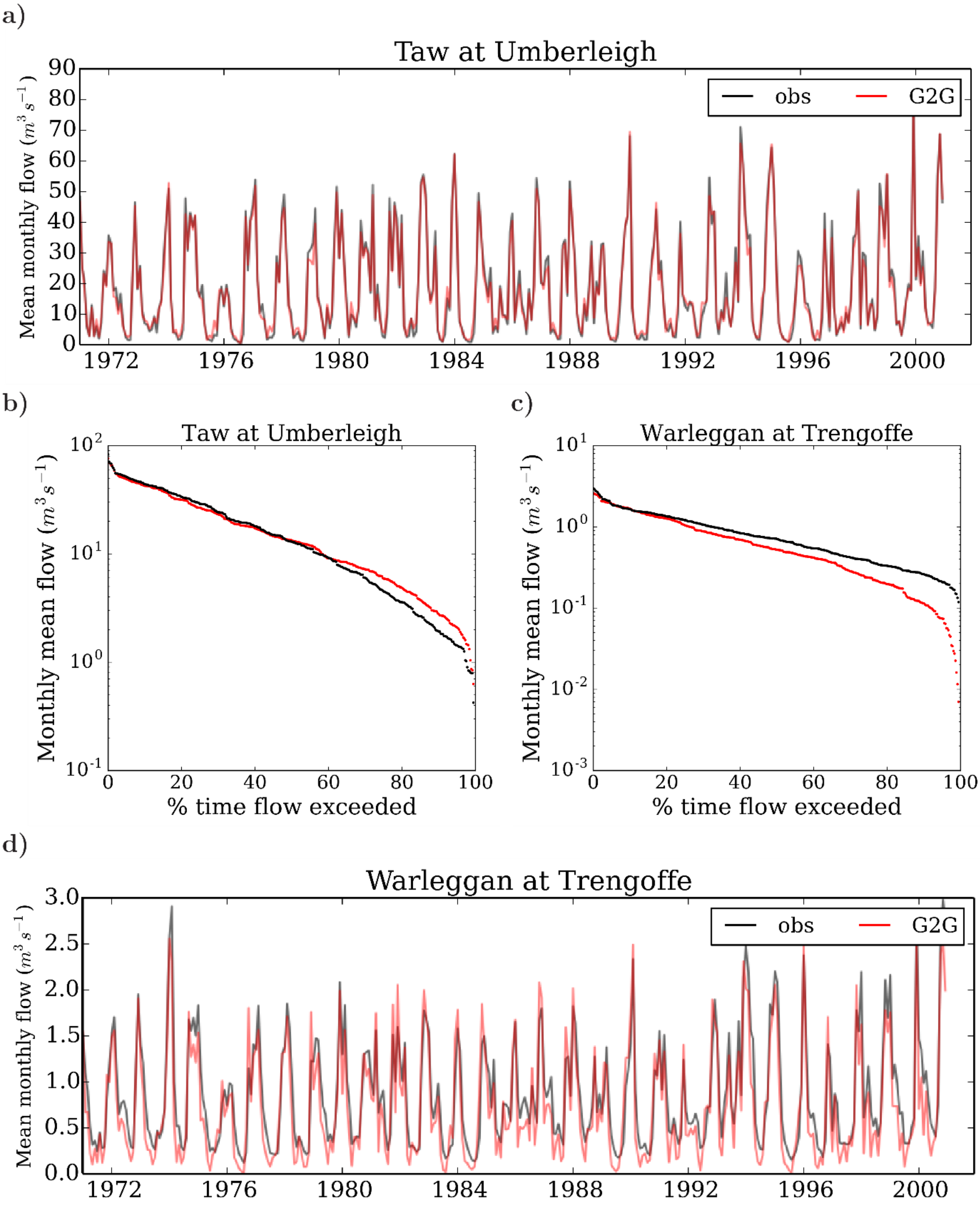

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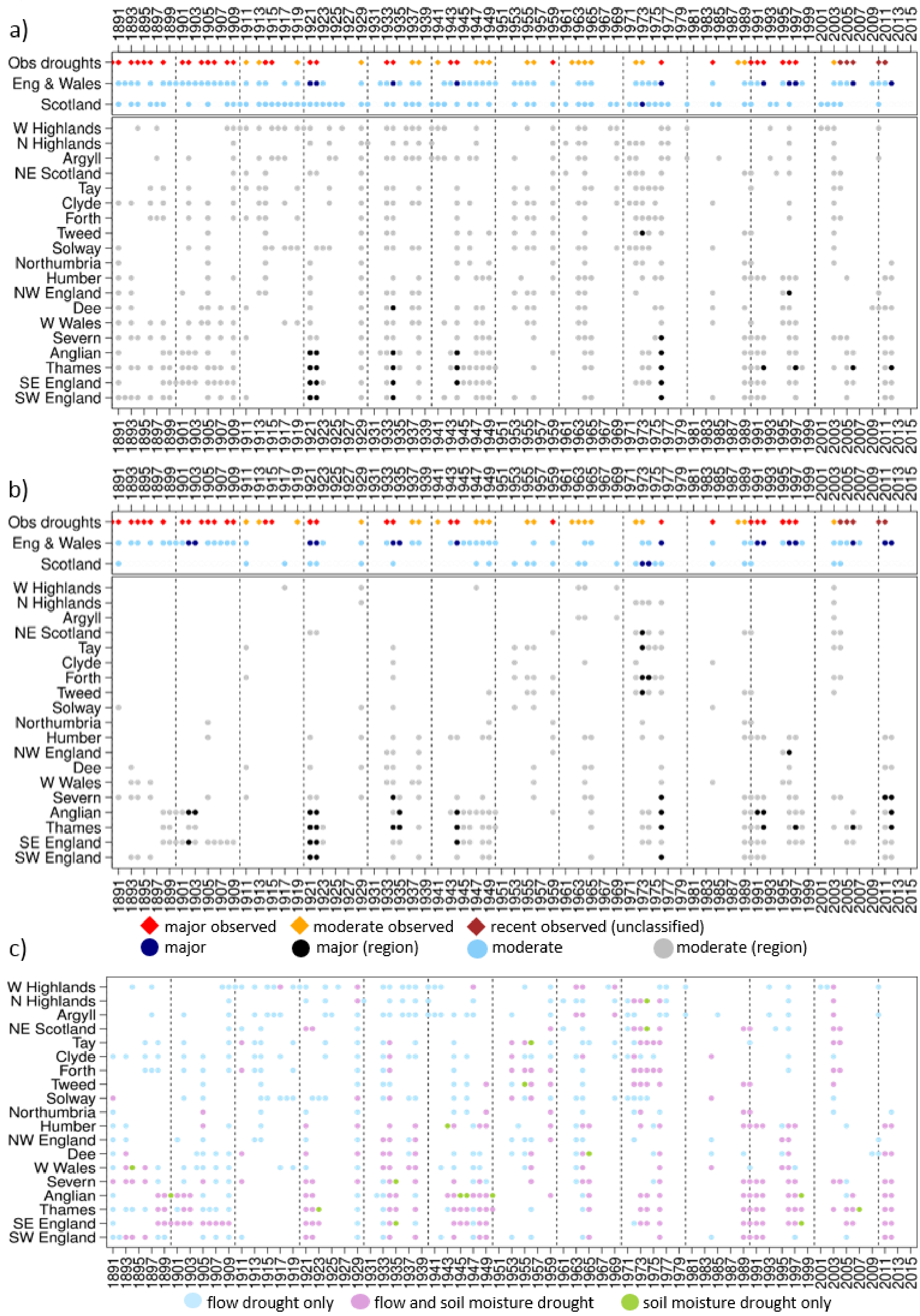

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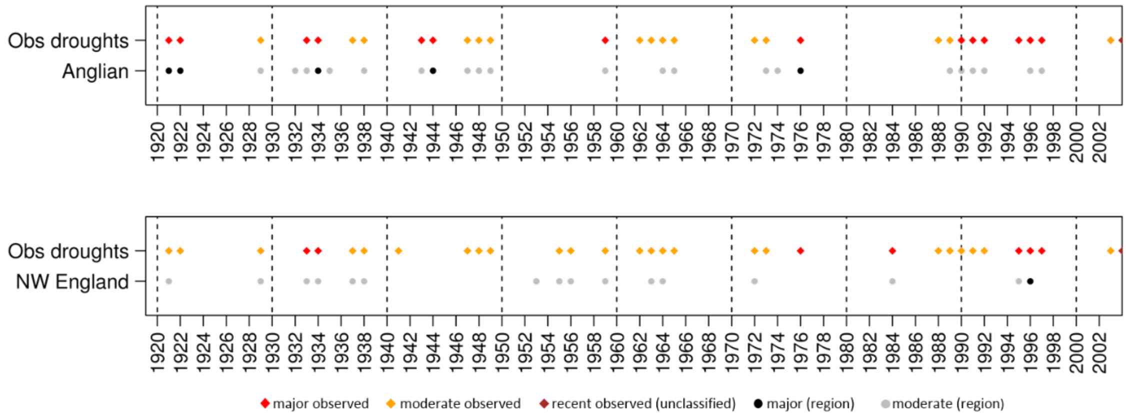
a)

b)



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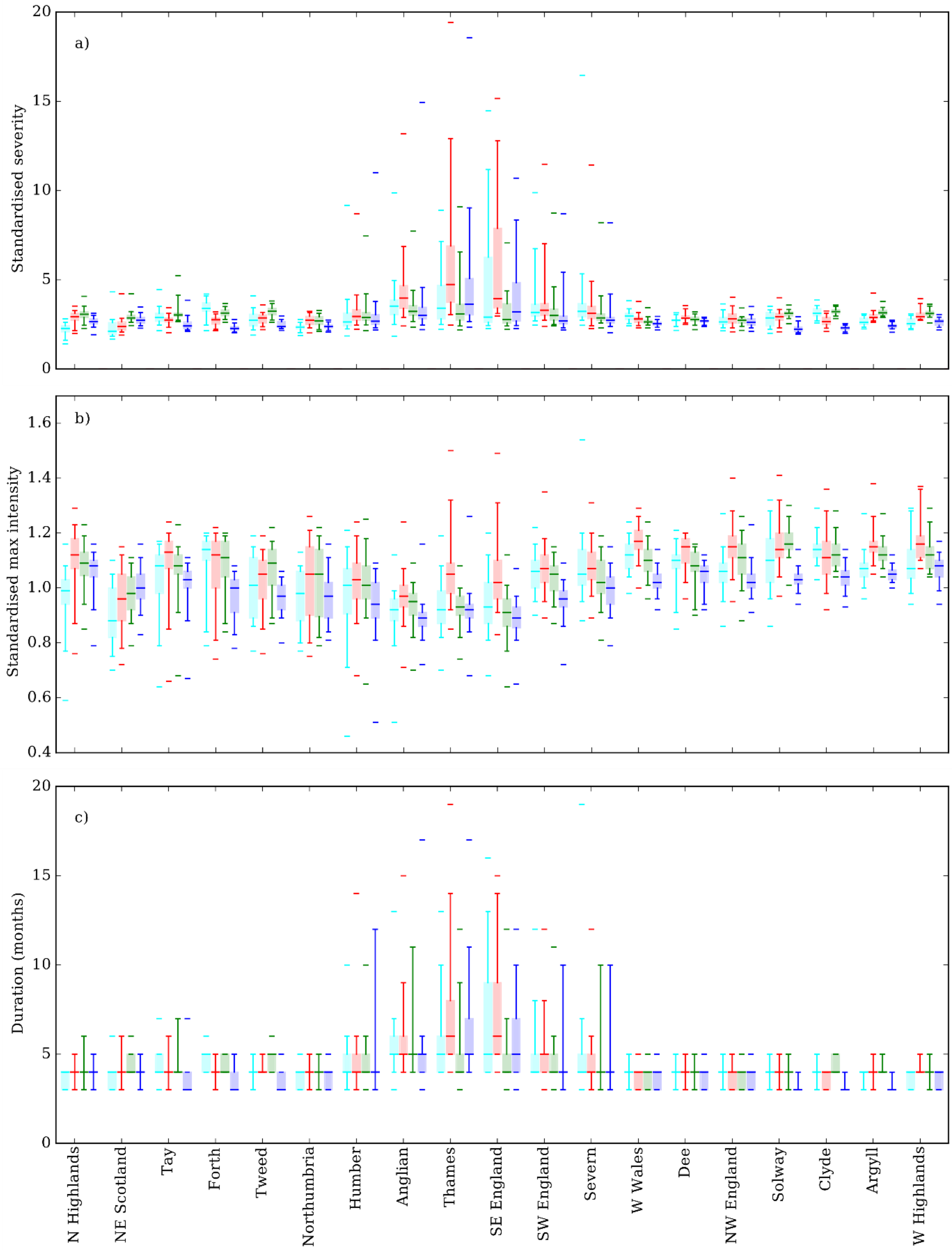

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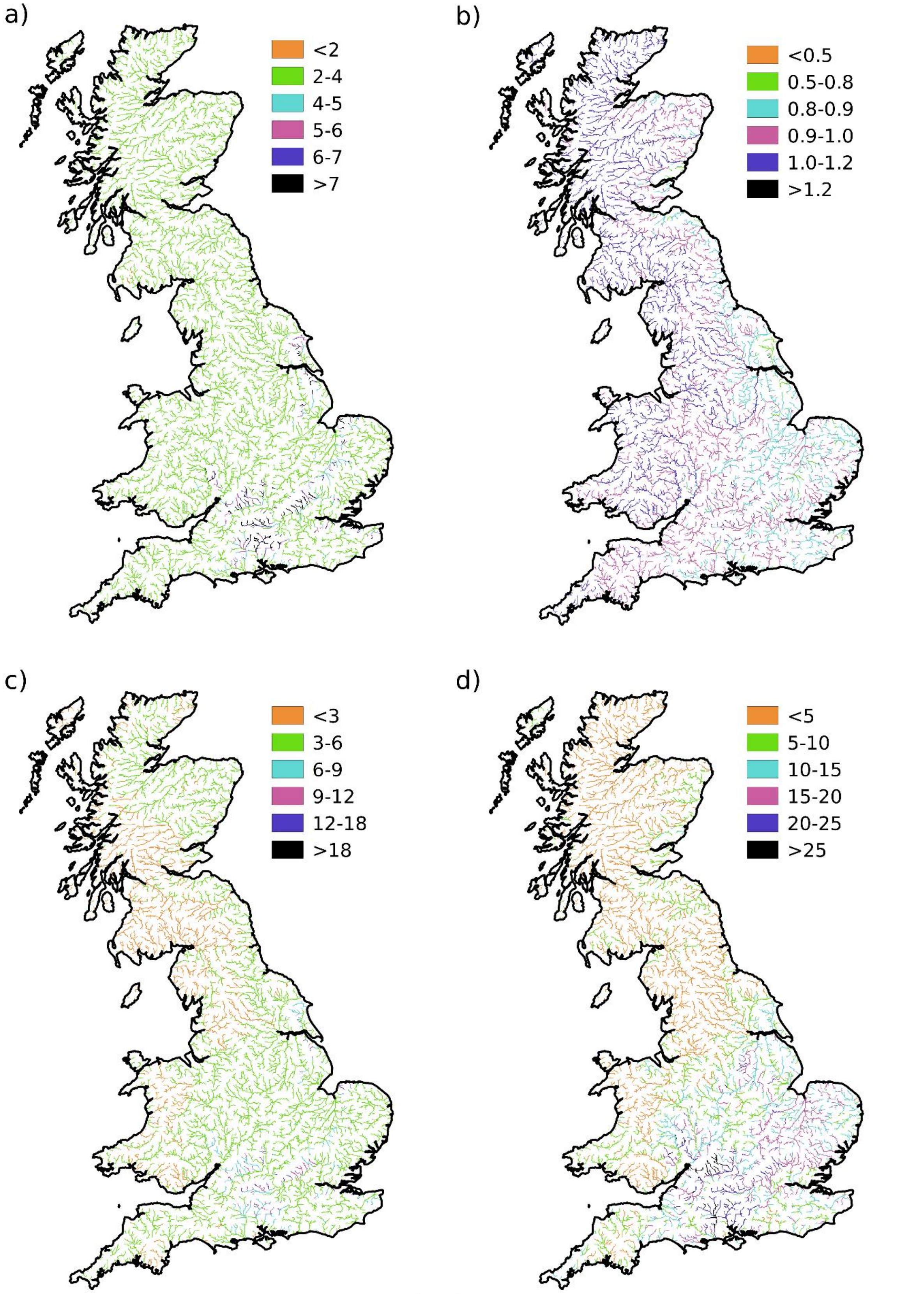

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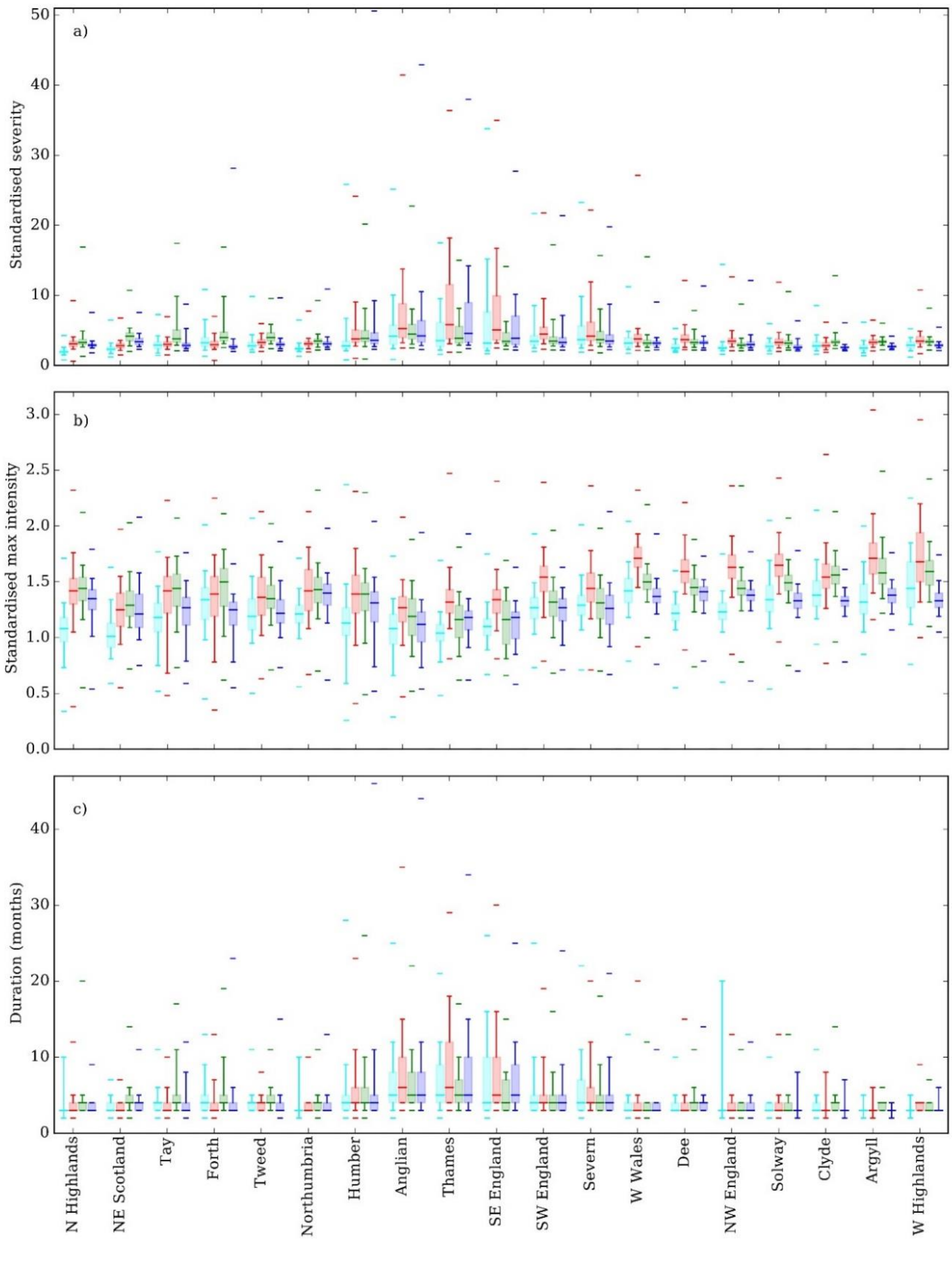

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Table 1: Historic droughts of England and Wales and the regions of East Anglia and North West England, based on Cole and Marsh (2006).

	England and Wales	East Anglia	North West England	Comment
Major				
	1891	✓ (moderate)	✓ (moderate)	
	1893-96	✓	✗	Classed as "modest" in North West England
	1898	✓ (moderate)	✗	
	1901-02	✓	✓ (moderate)	
	1904-06	✓ (moderate)	✓ (moderate)	
	1908-09	✓ (moderate)	✗	
	1914-15	✗	✓	
	1921-22	✓	✓ (moderate)	
	1933-34	✓	✓	
	1943-44	✓	✗	Classed as "modest" in North West England
	1959	✓	✓ (moderate)	
	1976	✓	✓	
	1984	✗	✓	Classed as "modest" in East Anglia
	1990-92	✓	✓ (moderate)	
	1995-97	✓	✓	
Moderate				
	1911	✓	✗	
	1913	✗	✓	
	1919	✓	✓	
	1929	✓	✓	
	1937-38	✓	✓	
	1941	✗	✓	East Anglia not affected
	1947-49	✓	✓	
	1955-56	✗	✓	Classed as "modest" in East Anglia
	1962-65	✓	✓	
	1972-73	✓	✓	
	1988-89	✓	✓	
	2003	✓	✓	
Unclassified				
	2004-06			Marsh et al., 2014
	2010-12			Kendon et al., 2013

National-scale analysis of simulated hydrological droughts (1891-2015)

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Supplementary Material

1 Study area and materials

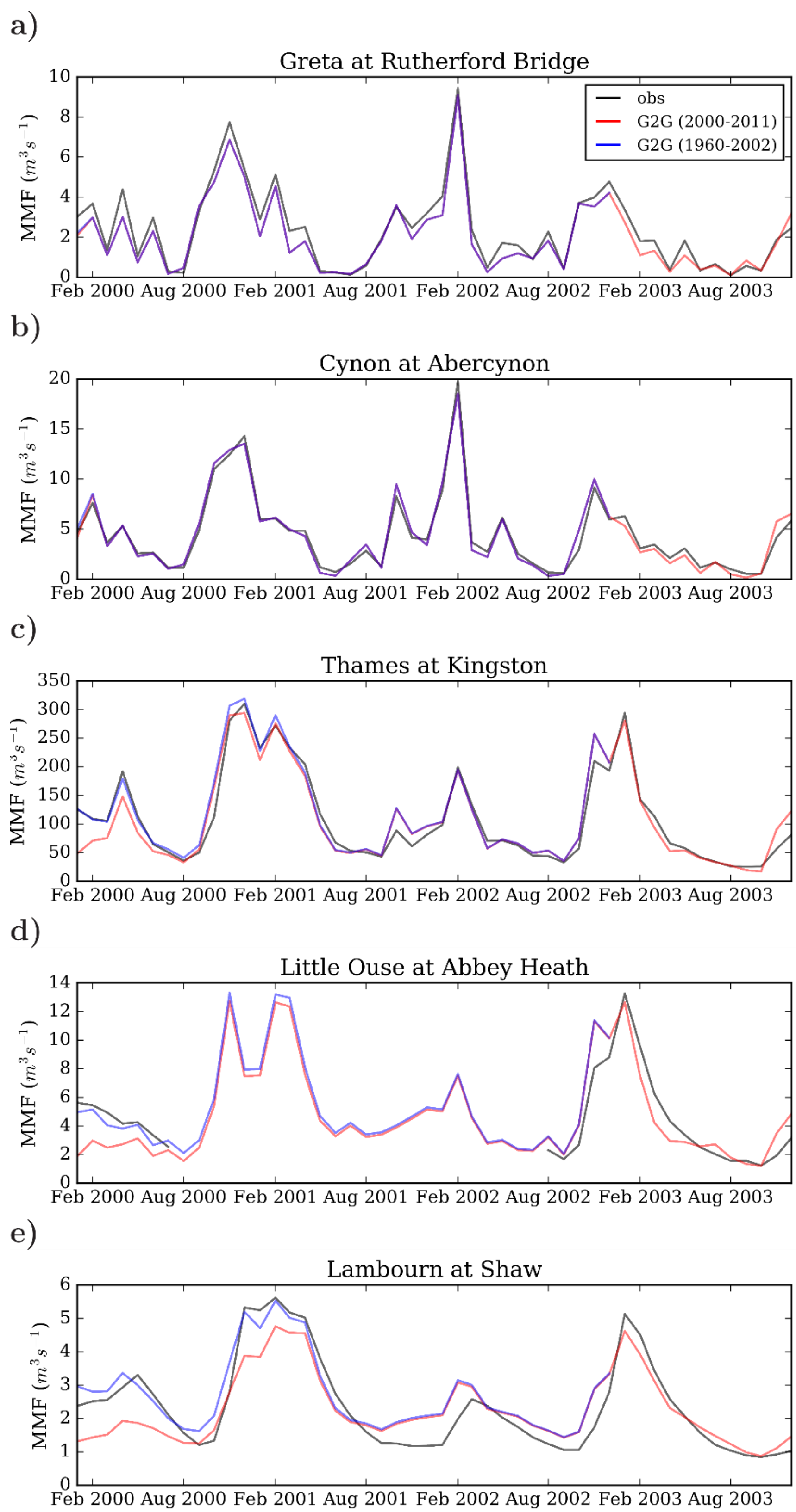
1.1 Hydrological model

Figure 1 shows examples of a 3 year overlap of a G2G run starting in 1960 and a G2G run starting in 2000, for 5 catchments with different values of base flow index. It shows that the simulations converge very quickly in most catchments and have converged in groundwater-dependent catchments by 2 years, illustrating that a model spin-up period of 2 years is sufficient.

2 Methodology

2.1 Hydrological model performance for low flows

Table 1 lists the 61 gauging stations used in the model performance assessment, with some of their catchment properties. Figure 2 shows the data availability (daily mean flow) for the 61 catchments used in the model performance assessment.

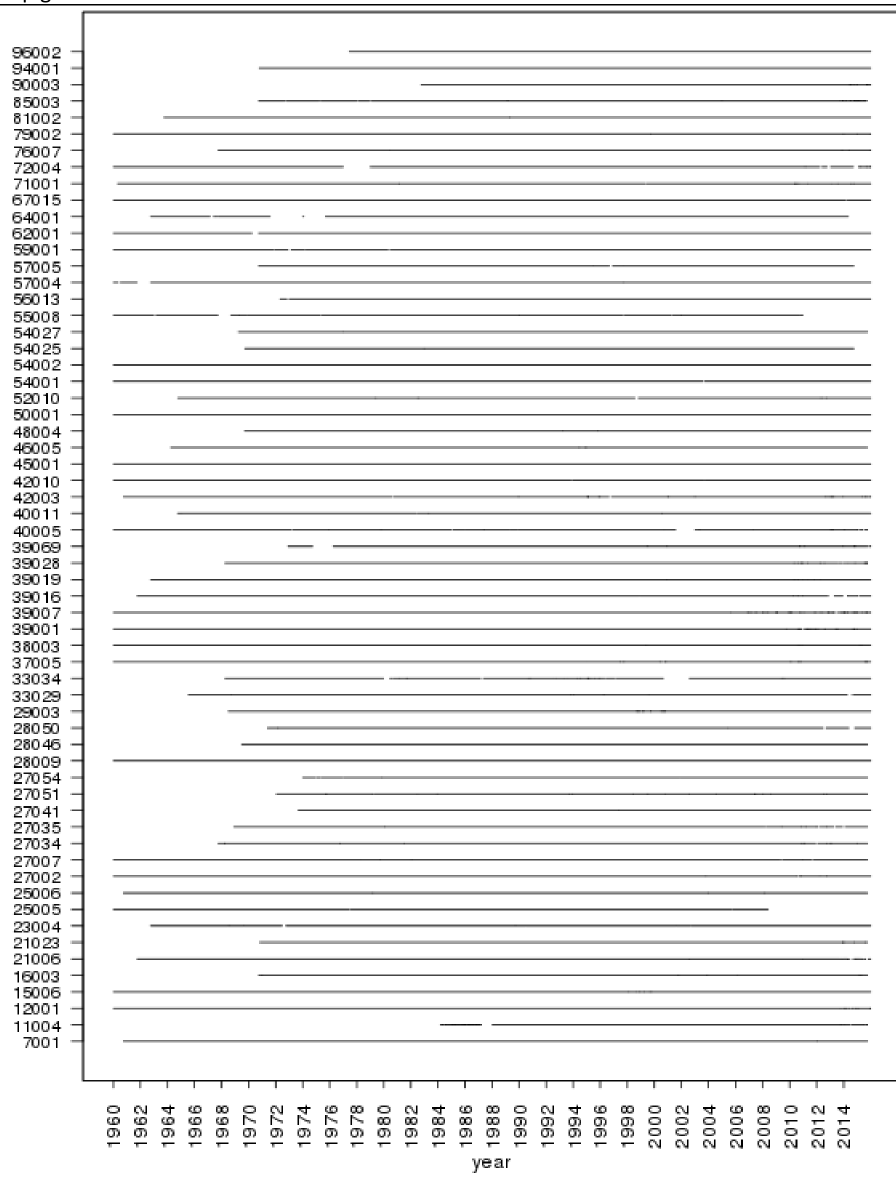


Supplementary Figure 1: Comparison of simulated and observed monthly mean river flow to illustrate that a spin up period of 2 years is sufficient for the G2G hydrological model, even in groundwater-dominated areas (Base flow index: Greta (0.21), Cynon (0.40), Thames (0.64), Little Ouse (0.8) and Lambourn (0.96)).

Supplementary Table 1: Details of the gauged locations for model performance assessment

Station number	River and location	Catchment area (km^2)	Benchmark	$SAAR_{61-90}$ (mm)	Median elevation (m)	BFI
07001	Findhorn at Shenachie	415.6	YES	1219	559	0.36
11004	Urie at Pitcaple	198.0	YES	870	196	0.75
12001	Dee at Woodend	1370.0	YES	1109	508	0.53
15006	Tay at Ballathie	4587.1	YES	1425	395	0.65
16003	Ruchill Water at Cultybraggan	99.5	YES	1889	390	0.29
21006	Tweed at Boleside	1500.0	YES	1166	341	0.51
21023	Leet Water at Coldstream	113.0	YES	671	74	0.34
23004	South Tyne at Haydon Bridge	751.1	YES	1148	333	0.34
25005	Leven at Leven Bridge	196.3	YES	725	92	0.42
25006	Greta at Rutherford Bridge	86.1	YES	1128	410	0.21
27002	Wharfe at Flint Mill Weir	758.9	NO	1161	258	0.39
27007	Ure at Westwick Lock	914.6	NO	1118	264	0.39
27034	Ure at Kilgram Bridge	510.2	NO	1342	368	0.32
27035	Aire at Kildwick Bridge	282.3	YES	1153	200	0.37
27041	Derwent at Buttercrambe	1586.0	NO	765	102	0.69
27051	Crimple at Burn Bridge	8.1	YES	856	171	0.31
27054	Hodge Beck at Cherry Farm	37.1	NO	947	268	0.53
28009	Trent at Colwick	7486.0	NO	761	118	0.64
28046	Dove at Izaak Walton	83.0	YES	1096	315	0.79
28050	Torne at Auckley	135.5	YES	615	23	0.67
29003	Lud at Louth	55.2	YES	699	89	0.9
33029	Stringside at Whitebridge	98.8	YES	629	20	0.84
33034	Little Ouse at Abbey Heath	688.5	NO	607	42	0.8
37005	Colne at Lexden	238.2	YES	566	68	0.52
38003	Mimram at Panshanger Park	133.9	YES	656	122	0.93
39001	Thames at Kingston	9948.0	NO	706	100	0.64
39007	Blackwater at Swallowfield	354.8	NO	707	80	0.67
39016	Kennet at Theale	1033.4	NO	759	153	0.87
39019	Lambourn at Shaw	234.1	YES	736	166	0.96
39028	Dun at Hungerford	101.3	YES	786	156	0.95
39069	Mole at Kinnersley Manor	142.0	NO	795	74	0.4
40005	Beult at Stilebridge	277.1	YES	690	39	0.24
40011	Great Stour at Horton	345.0	YES	747	75	0.7
42003	Lymington at Brockenhurst	98.9	YES	854	42	0.36
42010	Itchen at Highbridge & Allbrook Total	360.0	YES	833	107	0.96
45001	Exe at Thorverton	600.9	NO	1248	235	0.51
46005	East Dart at Bellever	21.5	YES	2088	458	0.44
48004	Warleggan at Trengoffe	25.3	YES	1442	232	0.71
50001	Taw at Umberleigh	826.2	NO	1155	168	0.43
52010	Brue at Lovington	135.2	YES	867	105	0.48
54001	Severn at Bewdley	4325.0	NO	913	127	0.53
54002	Avon at Evesham	2210.0	NO	654	96	0.52
54025	Dulas at Rhos-y-pentref	52.7	YES	1269	337	0.41
54027	Frome at Ebley Mill	198.0	NO	827	182	0.87
55008	Wye at Cefn Brwyn	10.6	NO	2453	480	0.31
56013	Yscir at Pont-Ar-Yscir	62.8	YES	1299	361	0.45
57004	Cynon at Abercynon	106.0	YES	1770	265	0.4
57005	Taff at Pontypridd	454.8	NO	1830	317	0.46
59001	Tawe at Ynystanglws	227.7	NO	1892	259	0.36

Station number	River and location	Catchment area (km²)	Benchmark	$SAAR_{61\text{-}90}$ (mm)	Median elevation (m)	BFI
62001	Teifi at Glanteifi	893.6	YES	1382	195	0.54
64001	Dyfi at Dyfi Bridge	471.3	YES	1834	261	0.39
67015	Dee at Manley Hall	1019.3	NO	1369	347	0.53
71001	Ribble at Samlesbury	1145.0	YES	1353	198	0.33
72004	Lune at Caton	983.0	NO	1523	264	0.32
76007	Eden at Sheepmount	2286.5	NO	1183	210	0.49
79002	Nith at Friars Carse	799.0	YES	1460	288	0.39
81002	Cree at Newton Stewart	368.0	YES	1760	212	0.28
85003	Falloch at Glen Falloch	80.3	YES	2842	446	0.16
90003	Nevis at Claggan	69.2	YES	2912	518	0.26
94001	Ewe at Poolewe	441.1	YES	2273	310	0.64
96002	Naver at Apigill	477.0	YES	1384	187	0.43



Supplementary Figure 2: Data availability: observed daily mean river flow for the 61 catchments (1960-2015). Values on the y-axis relate to the gauging station numbers in Supplementary Table 1. 87% (53) of the catchments have 95-100% data availability.

2.2 Drought identification (1891-2015)

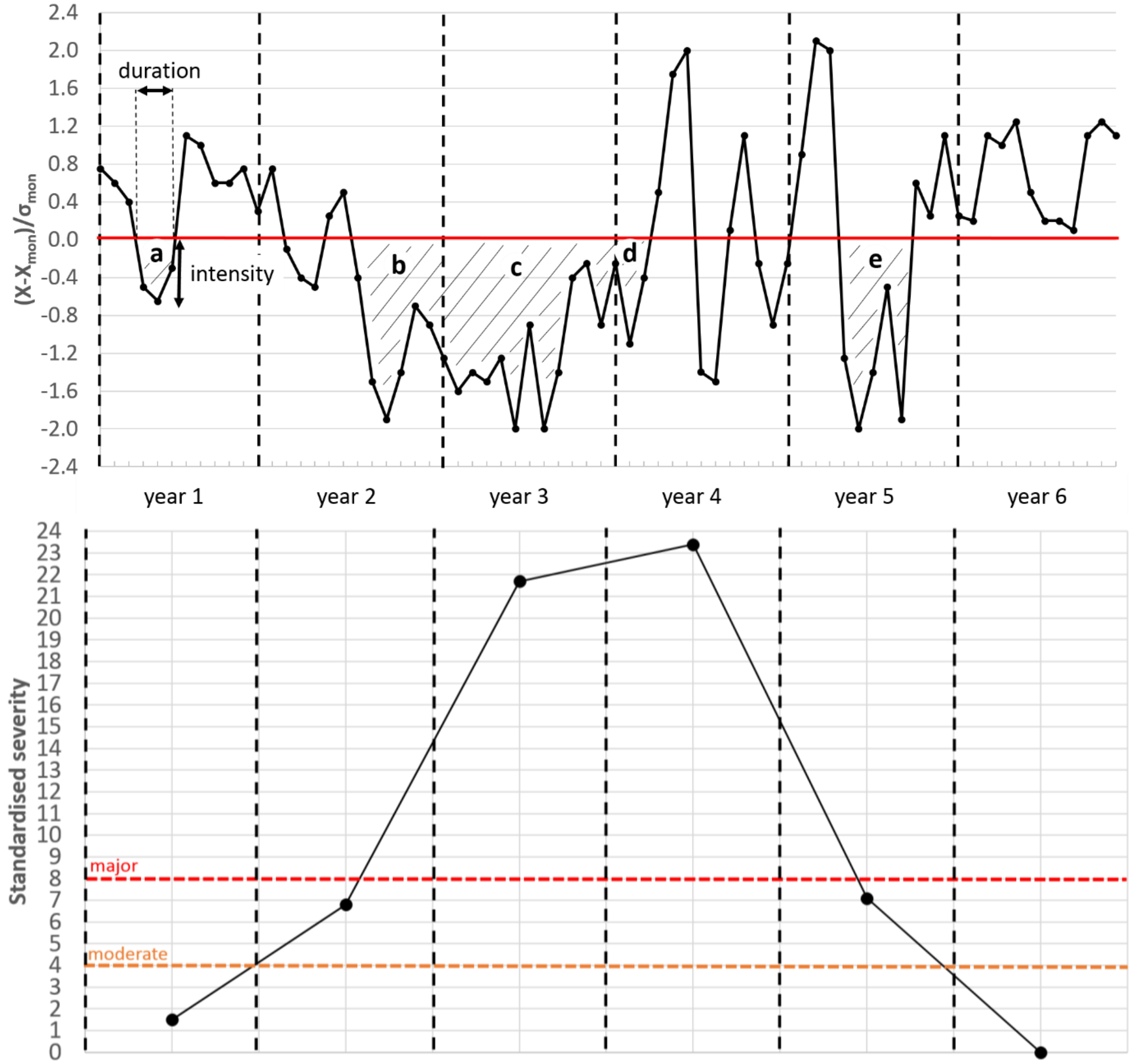
Droughts are identified using the threshold level method. The general threshold level method compares a time series of variable X to a threshold X_{thresh} (fixed or varying). A drought event starts when the variable falls below the threshold and continues until the threshold is exceeded again. However, there is no standard way of defining X_{thresh}. In this study a variable threshold is used, the long-term mean X_{mon} (1971-2000), this has the effect of removing the seasonality from the time series. In order to compare drought characteristics for different catchments the time series of anomalies $X - X_{mon}$ are standardised (Peters et al., 2003) by dividing by the long-term mean standard deviation for each month σ_{mon}. A “drought” is then defined as a period of time for which X is below normal (or $X - X_{mon} < 0$), i.e. as a deficit or difference from the long-term mean. The characteristics of a drought are then;

(i) standardised drought intensity — the deviation of $(X - X_{mon})/\sigma_{mon}$ below zero;
(ii) drought duration — the length of time below zero; and
(iii) standardised drought severity — duration multiplied by mean standardised intensity.

To identify particular drought years and enable annual mapping, the most severe simulated drought in each year is selected and national grids of drought characteristics (standardised severity, standardised maximum intensity and duration) are made.

Figure 3 shows an example time series to illustrate the threshold level method. Area (a) is identified as the most severe drought in year 1 with standardised severity of 1.5, standardised maximum intensity 0.7 and a duration of 3 months (Table 2). The drought ends in this year and no other event occurs. In year 2 a new drought starts, area (b) with standardised severity 6.8, standardised maximum intensity 1.9 and duration 6 months. This drought continues into year 3 (area c) with a cumulative severity of 21.7, standardised maximum intensity of 2 and duration of 18 months attributed to year 3. This extreme example then continues into the year 4 (area d) where the drought event terminates. The standardised severity for year 4 is then 23.4 with a standardised maximum intensity of 2 and duration of 21 months. In year 5 the most severe event is that denoted by area (e) and in year 6 there is not a drought because $(X - X_{mon})/\sigma_{mon}$ is greater than zero for the entire year.

To compare annual drought occurrence and severity to the historic observed droughts (Section 2.2), severity thresholds have been identified to classify the simulated droughts as major or moderate (Figure 3, bottom). The thresholds have been manually tuned so that the analysis of simulated flows and soil moisture identifies a good proportion of the observed drought years in 1891-2003, without identifying too many additional years as droughts. Thresholds are defined separately for river flow and soil moisture drought severity (river flow: major 8, moderate 4; soil moisture: major 16, moderate 8). It should be noted that the threshold selection is somewhat subjective, as is the major and moderate classification for observed droughts.



Supplementary Figure 3: Schematic of the threshold level method of drought identification, see also Table 2.

Supplementary Table 2: Drought characteristics from example time series (Figure 3).

Year the event is attributed to	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Area	a	b	b+c	b+c+d	e	NA
Severity of most severe event	1.5	6.8	21.7	23.4	7.1	0
Max intensity of most severe event	0.7	1.9	2	2	2	0
Duration of most severe event	3	6	18	21	5	0

3 Results

3.1 Hydrological model performance for low flows

Figure 4 shows the spatial distribution of the NSE and the NSE with the square root of flow for the 61 catchments (1971-2000). NSE is defined as

$$NSE = 1 - \frac{\sum (Q_t - M_t)^2}{\sum (Q_t - \overline{Q_t})^2}$$

and NSE with the square root of flow is defined as

$$NSEroot = 1 - \frac{\sum \left(\sqrt{Q_t} - \sqrt{M_t}\right)^2}{\sum \left(\sqrt{Q_t} - \sqrt{\overline{Q_t}}\right)^2},$$

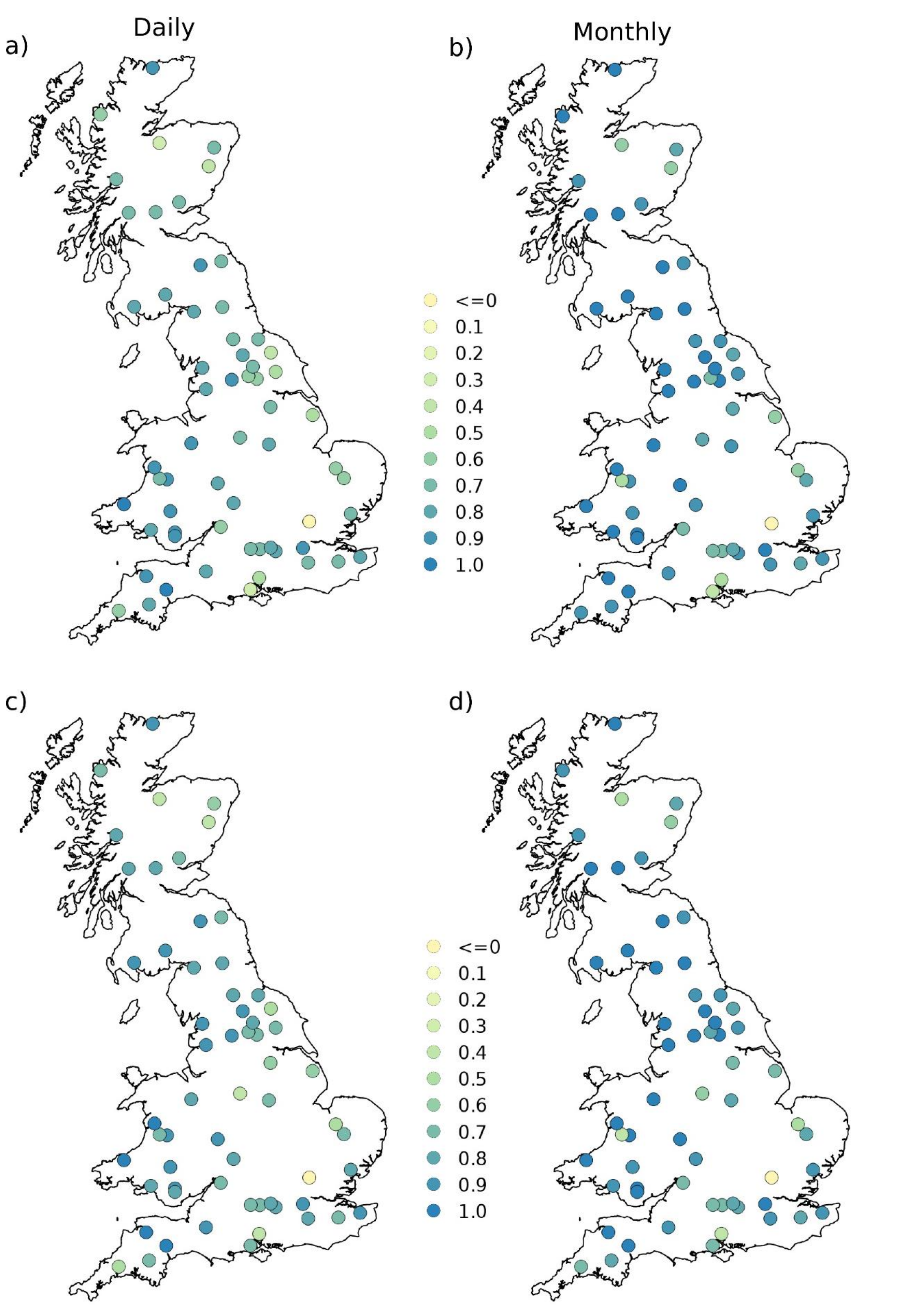
where Q_t are the observed flows, M_t are the modelled flows and t is the time (day or month). Figure 5 shows the NSElog for the two different G2G hydrological model runs described in Figure 1 (main text).

3.2 Drought identification (1891-2015)

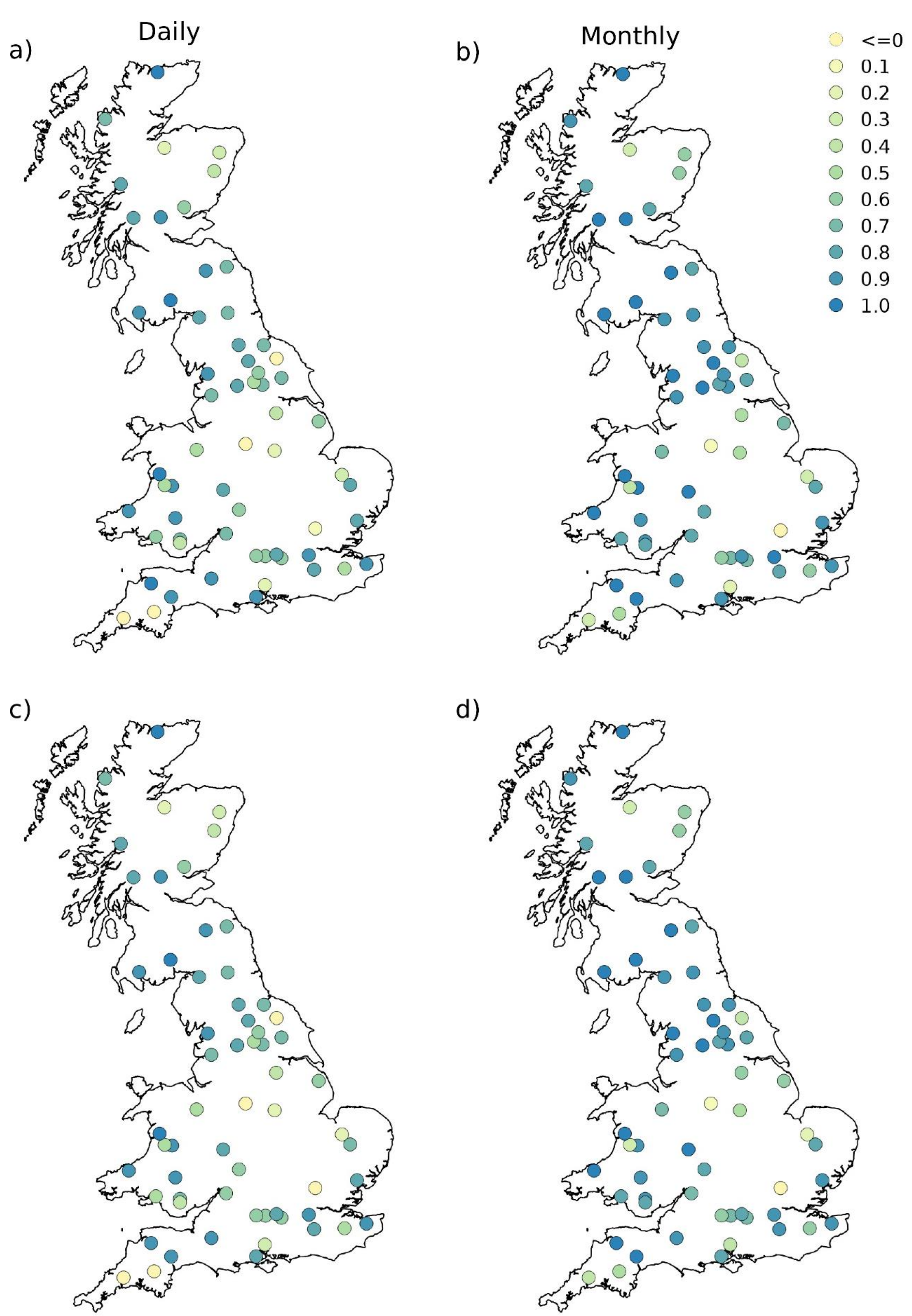
Table 3 lists the 19 river basins used in the drought identification, indicating which regions belong to England and Wales, and which to Scotland.

Supplementary Table 3: Separation of the 19 river basin regions into England & Wales and Scotland.

England & Wales	Scotland
Northumbria	W Highlands
Humber	N Highlands
NW England	Argyll
Dee	NE Scotland
W Wales	Tay
Severn	Clyde
Anglian	Forth
Thames	Tweed
SE England	Solway
SW England	



Supplementary Figure 4: Spatial distribution of NSE (a and b) and NSE with the square root of the flow (c and d) using daily (left) and monthly (right) time series for the 61 catchments (1971-2000).



Supplementary Figure 5: Spatial distribution of NSElog using MORECS PE (a and b) and Oudin corrected PE (c and d) using daily (left) and monthly (right) time series for the 61 catchments (1971-2000).