Dear Editor,

Re: Submission of revised manuscript ‘Historic hydrological droughts 1891-2015: systematic characterisation for a diverse set of catchments across the UK’ hess-2019-202 for HESS.

Thank you for the opportunity to revise our manuscript, especially the additional time in which to do so. We appreciate your comments as well as both reviewer comments and have responded to them below in italics, changes in the manuscript are marked with track changes below.

Yours sincerely,

Lucy Barker

Response to editor comments

Please replace as suggested Legg and McCarthy with the MetOffice references. Please also make sure that you refer to the newly published Smith et al (2019) paper where appropriate (e.g. the drought uncertainty consideration mentioned at the end of comment D) and that you include a short discussion of the uncertainties involved in your drought analyses.

We have removed the Legg & McCarthy (in preparation) reference and replaced it with references to the published datasets and also added the reference Hollis et al. (2019) which has just been published and describes the data rescue activities. We have added references to Smith et al. (2019) where appropriate. We have also added a short discussion around the uncertainties of using the SSI for these analyses in Section 4.3.

Also, I recommend adding as a supplement a list of the 108 catchments used in the study, with the most important metadata (river/gauge name, size, hydrolclimatic region, etc.) plus, if helpful, a reference to Barker et el (2018).

As you, and Gerry Spraggs, suggested we have added a list of the catchments and their properties to the Supplementary Information.

Response to reviewer 1

Major Comments

A) The paper has a considerable inconsistency in terms of citation style. Please check all the citations to make sure that e.g. Authors et al. (2019), (Authors et al., 2019) and so on is used in a consistent way. This will improve the readability of the paper! Some examples are listed in the technical comments.

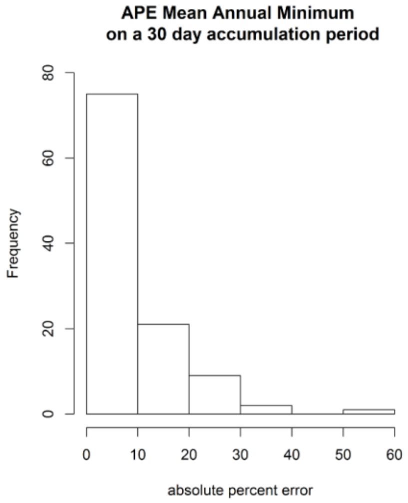
We have checked the citation style throughout and corrected where necessary.

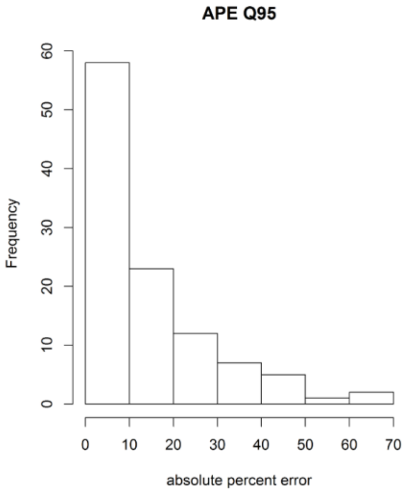
B) The reference Legg and McCarthy (prep.) (P05L09) is really problematic for me. As the readers have no chance to access this paper and "preparation" is for me different to "is submitted", the authors should at least give a short description of what is done in the Legg and McCarthy paper. After all, the model is fed by this data and therefore it is important to understand how meteorological data there is "rescued and digitized". The same is partly true for Smith et al. (2019) as this paper is still under review, isn't it? I suggest to give the reader whenever possible at least a brief description of data/method etc. instead of referring to unpublished studies. I can understand that this is not always easy to do, but it seems to be important to give the reader the chance to understand what has been done. It is also hard to understand how well the model performed (P6L18-L24) in detail, as no further information is given: Here my question is, how valuable is the modelling regarding low flows and streamflow droughts? Here more justification is needed.

We have removed all citations of in preparation papers. Smith et al. 2019 has been revised and accepted in HESS and the reference updated. The Legg & McCarthy reference has been replaced with references to the published datasets and the recently published Hollis et al. (2019).

C) Regarding the model GR4J I have some concerns regarding the details of the modelling approach. The 4-parameter version is used, if I understand the details in the give references correctly. From Smith et al. (2018) I cannot learn much about the 4 parameters and the functioning, Smith et al. (2019) certainly gives more information on the parameters, but how do you justify that this modelling approach is appropriate for your study propose (i.e. non-stationarity, long series, appropriate for low flows in different seasons)? Especially the slow component and its model representation is of great interest, as the slowest (groundwater) box in the model and its parameterization have potentially a high impact on drought characteristics (such as intensity, duration, deficit). Please comment on this issue (i.e. parameter sensitivity). Are there studies proofing that GR4J is a valuable modeling approach for low flow and drought analysis? Excluding snow and snowmelt processes might be reasonable, but that means that these processes are not relevant for low flows and streamflow droughts in none of the study catchments?

We have added more detail on this in Section 2.1 of the paper, including a reference to Caillouet et al (2017) who used the GR4J model to reconstruct low flows in France. Harrigan et al is also cited as they demonstrated good performance of the model across the UK. In response to other reviewer comments, we have added the list of metrics used by Smith et al in the calibration of the model used in this study, which include two low flows specific metrics: APE of Q95 and APE of Mean Annual Minimum on a 30 day accumulation period. Smith et al. (2019) conducted extensive parameter uncertainty estimation on the model, so we refer you to that paper for more detail. The Supplementary Info now includes plots of the performance of the model according to these metrics (Fig S1), and though the performance is varied across the country, we are satisfied with the results. The histograms below show that the majority of the LFBN catchments had low absolute percent error in MAM30 and Q95.





D) A provocative comment: You stated that historical droughts have been more severe than recent droughts (i.e. observed droughts) and a historical assessment is important to better understand the potential drought magnitude in a region/country. Contrary to that, I would argue that the use of water is adjusted to the water availability of the last, let‘s say, max. 30-40 years. All water users can only use available water and changes in water availability on a time scale of 3-4 decades influences (of course!) the water uses/water users. So, why is The Long Drought at the beginning of the last century relevant for the water users today? If you show these nice heatmaps with drought severity over 125 years you should also show a heatmap of uncertainty (i.e. comparison between observation period after 1950s and model period before 1950s) (cf. P25L05). Here, I speculate that the uncertainty assessment will soften your statements about historical drought magnitude, duration, intensity.

We appreciate your point that drought events may not have the same impacts now as they have done previously due to more resilient water supply and management systems. But regardless of water use, water resource managers look at natural water availability in their drought management plans. In the past, UK water supply drought plans have been based around planning for the worst event on record, and water companies must now plan for events outside of the historic record. Critical to these approaches is an understanding of events that have occurred in the past. Here we have identified past instances of events where natural water availability has been significantly lower, and for longer time periods than we have experienced in the recent past. Despite adjustments in water use to availability, extreme water deficits will still impact society, so information to better inform water resource managers on the characteristics of such events will always be valuable. The additional data provided by the reconstructed flow data provide this long view and enable the consistent identification and characterisation of droughts over the past 125 years. However, the uncertainty resulting in using only LHS1 (i.e. the best model run for each catchment as identified *by Smith et al. 2018) has been highlighted in Section 4.3. From a set of nine case study catchments, Smith et al (2019) found that parameter uncertainty had some impact on the extracted drought events, but mostly in the timing of droughts rather than the magnitude.*

Minor comments

- P02L05-10: How is the statement "historical records are still of fundamental importance in drought planning" justified? From my perspective Brown et al. highlights the lack of historical analysis, but the authors also referred to other studies in paper. However, I suggest to strengthen the study motivation here with more details on the value of historical data or analysis.
  As discussed in the response to the reviewer, this section of the introduction was intended to introduce the benefits of using of historic data in planning approaches; later in the introduction for example on pages 3 and 4, the motivation of this study is more clearly defined.

- P06L17-20: Would be helpful to give some more information about the criteria used to evaluate the performance.
  As discussed in the response to the reviewer, we have continued to direct the reader to Smith et al, 2019, but have listed the six evaluation metrics used in Section 2.1 of the paper.

- P06L26-30: What is the justification to select particularly these nine case study catchments? It is also not clear why case study catchments are used?
  As discussed in the response to the reviewer, the case study catchments were selected in order for results to be shown for individual catchments and were chosen to represent a range of catchment sizes/characteristics with one catchment per region as stated on P6L34-P7L3.

- P02L11: Just a suggestion: Are there some reference studies that have investigated major, severe droughts in UK? Could the paragraph better be linked to the P03L15-25) where some historical investigations have been listed?
  As discussed in the response the reviewer, Marsh et al. 20007 has been added to this sentence as an exemplar reference.

- P02L20: Is it warm/dry or warm and dry weather?
  This has been change to 'warm and dry weather'.

- P07L04: "end-month"? Is this the same as "right-aligned"?
  As discussed in the response to the reviewer, this has been clarified in the text with an example for the three and twelve month accumulation periods in the revised text.

- Sect 2.2.: I get the idea to have a short- and a long-term analysis (3 and 12 months). However, have you tested other accumulation periods? Is 12 month long enough to capture also long-term anomalies in the slowly reacting, GW dominated systems in South East England? As events with "less than three months were removed" (is this <3 month or <=3month?), I wonder why the SSI3 is used (as also a "seasonal focus" of the study is stated (P07L29) (see also comment below).
  As discussed in the response to the reviewer, we have clarified that results for additional accumulation periods are available via the UK Hydrological Drought Explorer on P26 L28-29. We also clarified that events of 1 and 2 months were removed on P8 L13-14. The SSI-3 was taken to be analogous to seasonal deficits as UK seasons are generally determined to be around three months long. SSI-12 was selected as it encompasses deficits over multiple seasons, representing longer term deficits as is stated on P7 L13-22, in the revised manuscript we added a comment to say that it may be appropriate to use other accumulation periods (including longer ones) in some cases – particularly in the south-east of England.

- What means “broadly north to south” exactly (P09L04)? Have you tried the heatmap with squares instead of rectangles (and with a fine border/stroke around the squares; this could improve the clarity of the graph, perhaps.). It would be also interesting to sort the catchments within each geographical group. North-to south is perhaps not really hydrological meaningful; what about a sorting along a low flow metric (e.g. Q90/Q50) to highlight differences in on-set and termination?
We carefully considered the recommendation of reviewers 1 and 2 to sort the catchments of the y-axis of Figure3/S1 etc.by Q90. However, we felt that the arrangement of the catchments from north to south using the NRFA station numbers to sort catchments (which as described in the response to the reviewer means they are arranged by hydrometric area, and therefore grouped by climatologically and hydrologically similar areas – see here for more info: https://nrfa.ceh.ac.uk/station-number and https://nrfa.ceh.ac.uk/hydrometric-areas) better reflects the aims of the paper in understanding when droughts occurred across the UK, and when and where they were most severe. We also did not want to introduce another metric (Q90) which is not used elsewhere in the paper that is a different in concept to the Standardised Streamflow Index used. We have therefore integrated the other suggestions made by the reviewer around moving the region labels to outside of the plotting area etc. but have left the catchments ordered as they were previously.

- Fig.4: Are the differences between maximum intensity (dot size) and mean deficit (colors) discussed?
These characteristics are described on P12L4-7.

- I am not an expert for historical droughts in UK, but is “The Long Drought” really a 20 year event without drought termination / interruptions? From Fig. 3 and Fig 10a, I have the impression that there are also a lot of “yellow” and “white” segments in the heatmap (e.g. 1904 wasn‘t really a dry year).
This point was also raised by reviewer 2. We have amended any reference to the ‘Long Drought’ to “the ‘Long Drought’ period” to reflect that it was a period within which drought conditions occurred (rather than a continuous period of drought) as is shown in Figures 3 and 10a.

- Fig. 6 is really a nice idea, but it is hard to understand and it take me a while to understand the encodings used in the Figure. I suggest to use a UK-matrix with 9 columns (i.e. events) and 4 rows (i.e. drought characteristics). Then in each subplot all catchments with mild grey dots overplotted by the top ranking catchments in black color. Would improve the clarity of the Fig.
We have added an additional key to Figure 6, and subsequent plots in the same style, to illustrate which characteristic each colour and circle style represents. We think this has made these figures easier to interpret.

- Would be interesting to quantify the differences between the MCW2007 drought magnitude and the (more severe) droughts on catchment or regional scale (Sect 4.1), e.g. what is the difference of a very critical drought situation in a specific catchment compared to the “national” drought magnitude?
As we discuss in the response to the reviewer, the focus of this paper was the consistent identification, characterisation and ranking of events at the national scale. We have highlighted on P27L34 that future work should assess drought severity in a more holistic way, by including rainfall, groundwater and water supply analyses, at the national and regional scale.

- The authors stated that SSI-3 and SSI-12 are a good choice to identify different drought types (P23). Is this a general recommendation for other studies (3- and 12-months)? If not, what might be a good (and sufficient) set of different SSI-n to capture the variability of historical droughts?
We use the 3 and 12 month accumulation period to characterise single season (3-month) and multi-season annual (SSI-12) hydrological droughts as described on P7 L13-16, and would recommend these accumulation periods for these purposes. However, the exact choice of accumulation period in future studies will depend on the motivation and application of research, if for example, you are interested in multi-year droughts you may choose to look at

accumulation periods of 12, 24, 36 months etc.) – we have added a comment to this effect on P7 L16-22. However, we felt that the use and presentation of additional accumulation periods was out of the scope of this paper.

- Sect 4.3 is a little bit long and could be more condensed. The authors discussed potential limitations of their work (e.g. non-stationarity, model uncertainty), but here I missed a clear link to the (own) study results.
  We have condensed Section 4.3 in the revised paper whilst introducing other points recommended by the other reviewers.

Technical Comments

1. P06L05: Smith et al. (2019) also assessed
   Citation style updated.

2. P06L09: by Smith et al. (2018)
   Citation style updated.

3. P06L11: Low Flow Benchmark Network (LFBN).
   Low Flow capitalised.

4. P06L17: reconstructed by Smith et al. (2018), which include the LFBN, performed
   Text updated as suggested.

5. For readers from outside UK a short explanation of "Anglian" would be helpful (P09L23).
   Anglian changed to ANG to make clear it refers to the hydroclimate region shown in Figure 1. Updated all mentions of regions to the acronyms used in Figure 1 for clarity.

6. P11L03-04: two times "accumulation period"?
   Grammar of sentence improved and two mentions of accumulation periods removed.

7. lower maximum intensity is more severe? (P11L04/05). Terms should be revised here.
   Clarified that lower maximum intensity is a more severe event.

8. Fig.4: The 45 degree axis labels are hard to read, thin grid lines or a lollipop graph instead of bubble graph could improve the readability. If you referred to pre-obs and obs-period than a vertical line to distinguish both periods would be beneficial. Have you tried a lollipop chart here, i.e. vertical lines between dots and x-axis might improve the readability?
   Plots amended so that x-axis labels are at 90^o and so there is a vertical line between the points and the x-axis. We did not add the vertical line to mark the pre-observation/observation period but have added a comment to the text to make clear when we are referring to.

9. Remove leading white spaces in (*Figure 5. . .) on page 12.
   Formatting issue resolved.

Response to reviewer 2

General comments:

Little information is given on the basic datasets used for driving the hydrological model. Please elaborate in more detail on the digitized meteorological data. Is this raw data or have they undergone a homogenization procedure? I also think that a reference for a paper in "preparation" is not suitable. Moreover I think that there has to be a more in-depth description of the hydrological modelling. E.g. Smith et al. (2019) used six evaluation metrics some of the specific for low flows. What are these metrics and what is the performance? Please provide some information in this respect.

We have removed the reference to the in preparation Legg & McCarthy reference and replaced it with references to the published datasets as stated in the response to the reviewer and a newly published paper Hollis et al. (2019) which describes the digitisation process of the data rescue and the datasets.

We have added a list of the model performance metrics used by Smith et al. (2019) to assess model performance, and have added a figure to the supplementary information (Figure S1) which maps the six LHS1 model performance metrics for the 108 LFBN catchments.

You use the SSI as a standardized hydrological drought indicator. What about the uncertainties considering the fitting of the distribution and how do these translate in terms of derived drought metrics? Since you use mostly rankings of the top events it is rather crucial how the fitting performs particularly at the tails of the distribution. Could you just exemplarily give an indication of possible change in the ranking of some drought metric from fitting uncertainty?

As discussed in the response to the reviewer, we have added more information on the benefits of using the Tweedie distribution to the revised paper on P7 L24-28, and a brief discussion of the uncertainties to the discussion on P26 L33-P27 L1.

Figure layout:

For Figures 3, 5 and 10 I suggest to place the acronyms for the region outside the plot area along the y-axis for better readability. Also rethink the arrangement of catchments along the y-axis, perhaps there is a better way than a strict North/South (driven by climate) alignment (e.g. low flow characteristics).

We have moved the region labels to the y-axis, making the plot easier to read.

We carefully considered the recommendation of reviewers 1 and 2 to sort the catchments of the y-axis of Figure3/S1 etc.by Q90. However, we felt that the arrangement of the catchments from north to south using the NRFA station numbers to sort catchments (which as described in the response to the reviewer means they are arranged my hydrometric area, and therefore grouped by climatologically and hydrologically similar areas – see here for more info: https://nrfa.ceh.ac.uk/station-number and https://nrfa.ceh.ac.uk/hydrometric-areas) better reflects the aims of the paper in understanding when droughts occurred across the UK, and when and where they were most severe. We also did not want to introduce another metric which is not used elsewhere in the paper that is a different in concept to the standardised Streamflow Index used. We have therefore made the other suggestions around moving the region labels to outside of the plotting area etc. but left the catchments ordered as they were previously.

Figure 5: The colorbar as a gradient from red to yellow is in general appropriate for this kind of data in terms of figure layout guidelines. However, since the displayed data is a ranking, I think that the reader would like to see first of all where the top ranked events are. This is not easy in this case. Perhaps you could try a colorbar with more colors? (in R: RColorBrewer palette "Spectral") Or combine two colorbars, one for the top 3 (or 5?) and one for the rest. Don't know how it would look, but it is perhaps worth a try to get the essential information better across.

We have added a dark purple to the colour palette used (as the colour for rank 1), and removed one of the red colours. We feel this makes it easier to separate the different ranks and the plot easier to interpret. Palettes with too many colours, such as "spectral", are not suitable for colour-blind readers.

Several times across the manuscript I stumbled over the terms droughts, drought event or drought periods. I'd like to see more consistency with these terms. The list of major droughts (Table 1) is mostly termed events, however, the 1890-1910 period is not an event from an event definition point of view. This comes rather clear in Figure 10a, where the "long drought" is clearly made up of several individual events(!) all of them with a distinct beginning and end. On the other hand, 1921 (Figure 10b) is clearly an event itself, it has a distinct beginning and end. I suggest to define the names of the major droughts as in Table 1 and stick to the terms, e.g. "1890-1910 drought period", "1921 event", "1976 event", etc. I think that an event stretching over several years could be termed as the "year xxxx event", with the year being that with maximum drought intensity for example, which has to be defined obviously.

We have referred to the Long Drought as "the 'Long Drought' period" throughout, we hope that this reflects that is a name given to the period as a whole. We have continued to refer to the remaining events as start year – end year as discussed in the response to the reviewer.

Specific comments:

P2L20: ". . .short periods of warm and dry weather. . ."

This has been changed as suggested. P2L24: "Moreover, greater climatic variability could mean an increase in persistent blocking episodes and multi-year droughts" please provide a reference for this statement.

We have cited Folland et al. 2015 in this sentence.

P6L5: "Smith et al. (2019) also" please be generally careful with the citations, there are some other inconsistencies.

The citation style here has been corrected and remaining citations checked and corrected where necessary.

P6L11: "Low Flow Benchmark Network (LFBN)"

Low Flow has been capitalised as suggested.

P11L3: suggestion: "For both time scales considered, events tend. . ."

We have modified this sentence to improve the grammar.

P19L6: ". . . e.g. 1895 saw extreme flow deficits across Scotland and Northern Ireland. . ."

This sentence has been changed as suggested.

P22L10: In this section some recent research would be appropriate to cite, since there are some events detected in the present paper also listed as extreme droughts in other regions of Europe for example in:

Hanel, M., Rakovec, O., Markonis, Y., Máca, P., Samaniego, L., KyselÃ¡, J., & Kumar, R. (2018). Revisiting the recent European droughts from a long-term perspective. Scientific Reports, 8(1). https://doi.org/10.1038/s41598-018-27464-4

Haslinger, K., & Blöschl, G. (2017). Space-Time Patterns of Meteorological Drought Events in the European Greater Alpine Region Over the Past 210 Years. Water Resources Research, 53(11), 9807–9823. https://doi.org/10.1002/2017WR020797

We have added reference to Hanel et al. (2018) to Section 4.1 of the revised manuscript, we felt that Haslinger et al. (2017), although had similar and related results was too specific in spatial coverage, and so on reflection did not add this reference to the revised manuscript.

Response to Gerry Spraggs

In the abstract you could say '108 near natural catchments'. I think it would be useful for water managers to know up-front the type of catchment you are analysing as they deal with a whole range of catchment conditions.

We have added that the 108 catchments were near-natural to the abstract.

page6 lines9-16 To expand on the previous comment, much of the time water resource planning has to deal with non-natural flows. For this situation your method would require naturalisation of recorded flow series before model calibration and flow series extension. Alternatively, model calibration with artificial influences included. It's obviously achievable but a longer procedure with more room for introducing error.

In response to the comments of the other reviewers, Section 4.3 was condensed and so this comment was not added in the end, although clearly will be an extremely important consideration of any further work.

page6 line23 Would it be worth appending a list in the supplement of the 108 catchments shown in Figure 1? I found myself trying to work out which Anglian catchments were used and others may want to do the same in other parts of the UK.

A table of the 108 catchments used here has been added to the Supplementary Information (Table S1).

Figure 2. The Maximum Intensity appears be dimensioned in units of time. Should it be defined by say a horizontal dotted line from the lowest SSI point (-2) to the Y axis, plus a vertical line (with arrowheads at each end) from the dotted line to SSI zero line? The dimension would then be SSI.

We have amended the plot as suggested.

page14 lines7-8 1989-90 was severe in East Anglia, particularly for groundwater. So are you saying '...with the latter being particularly severe for the 1990s as a whole'?

This has been clarified in the revised paper as discussed in the response to the reviewer.

Figure 6. Looking at Anglian region it is clear that use of different characteristics identifies different droughts i.e.1891-1910, 1920-22, 1975-6, 1990-92. Water resource modelling often shows that there is sometimes very little difference between major droughts when it comes to defining system yield for use in the supply-demand balance. If you look at Fig. 10 of our 2015 paper you can see that simulated reservoir drawdown at Grafham was very similar for 4 droughts: 1920-1, 1933-4, 1944-7 and 1975-6. Tweaks to the WR model parameters, e.g. frequency of supply restrictions, have been shown to invoke one or other of these droughts as critical. The point I'm making is that only by simulating a WR system over the whole historic series (behavioural analysis) will the critical drought be found - I think you say this later in the paper!

As stated in the response to the reviewer, here we were concerned with which hydrological droughts were the most severe without the effect of management and without considering their impacts on water resources, society or the environment etc. We feel this is an important first step before impacts can be fully assessed. As you point out, we make this point later in the paper (P27 L34- P28 L4). It would be an interesting next step to run the reconstructions through supply system models to assess the impact of these droughts on water supplies at the national scale.

page20 line11 better to stick with 'near natural catchments'?

Changed as suggested.

page22 lines5-6 we found 1989-92 to be the most severe in the north of the Anglian region, including the Lud catchment, not the whole region (2015 paper Table 2). It ranked only 9th for Alton in Suffolk. But as you point out: different method, different durations.

We have clarified that this statement referred only to the River Lud as discussed in the response to the reviewer.

page23 lines 6-10 1943-46 drought significant in west of Anglian region (2015 paper abstract and Table 2 for Grafham 24 months period)

We have added to the revised paper that Spraggs et al. 2015 also found this event to be significant for the Anglian region.

page24 lines12-13 Extending the hydrological series back from 1920 to 1800 did not introduce different critical droughts - they all remained post-1920 (2015 paper Table 3). It didn't change the approach or methodology, so could you delete 'approaches' and just say '...planning in particular water...'?

Changed as suggested.

page 24 lines17-21 Totally agree! I noted this in our 2015 paper Conclusions point 6.

We appreciate that this was noted by Spraggs et al. (2015) but on reflection we felt it was appropriate to reference this paper in this sentence, we have however, noted in many other places the synergies between the two papers.

page 25 lines15-22 'non-stationarities in catchment response or land use change' may not be an issue for water resource planning. Current or projected future (planned) artificial catchment influences can be added to an extended naturalised series for use in water resource models. Catchment change etc. would of course be important for corroboration with documentary evidence.

As noted in the response to the reviewer, we appreciate that historic changes in catchment response or land use change may not an issue for water resources planning, but as we state in the paper, modelling approaches do not account for changes in land use etc. over time and as such it is an important caveat to make for the reconstructed flows as they may not fully represent *the past. It is also an important reason as to why the maintenance of long-term records and the digitisation and rescue of data are of critical importance for hydrology.*

The first referee questions why the choice of 3 and 12 month SSI. From the water resources planning and management perspective longer droughts have been a concern, notably during the 2010-12 episode, with the ever increasing impact of global warming. So, although drought structure under a changing climate is conjectural, 24 and 36 month SSI would be interesting!

We have added a sentence to describe the necessity of assessing additional accumulation periods based on the location and the event of interest to P7L17-19 We have also noted that results for additional accumulation periods can be viewed on the UK Hydrological Drought Explorer (https://shiny-apps.ceh.ac.uk/hydro_drought_explorer/) on P26 L27.

And a few typos:

page2 line34 'quantify and understand'?

Changed as suggested.

page8 line12 delete the ', they'

Changed as suggested.

page 12 line20 you use the word 'record' when technically the earlier data is not recorded, so perhaps say 'period'? Anywhere else in paper?

Changed to say earlier part of the reconstructed series.

page16 line14 'major droughts for'?

Changed as suggested.

page17 line18 1890-1910

Corrected.

page17 line 21 'regularly'

Corrected.

page17 line29 At

Corrected.

page23 line19 Should it be Figure 5 or 7?

Figure numbers corrected.

References

Bachmair, S., Svensson, C., Hannaford, J., Barker, L., and Stahl, K.: A quantitative analysis to objectively appraise drought indicators and model drought impacts, Hydrology and Earth System Sciences, 20, 2589-2609, 2016.

Barker, L. J., Hannaford, J., Chiverton, A., and Svensson, C.: From meteorological to hydrological drought using standardised indicators, Hydrology and Earth System Sciences, 20, 2483-2505, 2016.

Barker, L. J., Smith, K. A., Svensson, C., Tanguy, M., and Hannaford, J.: Historic Standardised Streamflow Index (SSI) using Tweedie distribution with standard period 1961-2010 for 303 UK catchments (1891-2015), NERC Environmental Information Data Centre, 10.5285/58ef13a9-539f-46e5-88ad-c89274191ff9, 2018.

Broderick, C., Matthews, T., Wilby, R. L., Bastola, S., and Murphy, C.: Transferability of hydrological models and ensemble averaging methods between contrasting climatic periods, Water Resources Research, 52, 8343-8373, doi:10.1002/2016WR018850, 2016.

Caillouet, L., Vidal, J. P., Sauquet, E., Devers, A., and Graff, B.: Ensemble reconstruction of spatio-temporal extreme low-flow events in France since 1871, Hydrol. Earth Syst. Sci., 21, 2923-2951, 10.5194/hess-21-2923-2017, 2017.

Folland, C. K., Hannaford, J., Bloomfield, J. P., Kendon, M., Svensson, C., Marchant, B. P., Prior, J., and Wallace, E.: Multi-annual droughts in the English Lowlands: a review of their characteristics and climate drivers in the winter half-year, Hydrol. Earth Syst. Sci., 19, 2353-2375, https://doi.org/10.5194/hess-19-2353-2015, 2015.

Hanel, M., Rakovec, O., Markonis, Y., Máca, P., Samaniego, L., Kyselý, J., and Kumar, R.: Revisiting the recent European droughts from a long-term perspective, Scientific Reports, 8, 9499, 10.1038/s41598-018-27464-4, 2018.

Harrigan, S., Prudhomme, C., Parry, S., Smith, K., and Tanguy, M.: Benchmarking ensemble streamflow prediction skill in the UK, Hydrology and Earth System Sciences, 22, 2023-2039, 2018.

Haslinger, K. and G. Blöschl (2017). "Space-Time Patterns of Meteorological Drought Events in the European Greater Alpine Region Over the Past 210 Years." Water Resources Research 53(11): 9807-9823.

Hollis, D., McCarthy, M., Kendon, M., Legg, T., and Simpson, I.: HadUK-Grid—A new UK dataset of gridded climate observations, Geoscience Data Journal, 0, 10.1002/gdj3.78, 2019.

Met Office: HadUK-Grid gridded and regional average climate observations for the UK, Centre for Environmental Data Analysis, 10.5285/4dc8450d889a491ebb20e724debe2dfb, 2018.

Met Office: MIDAS Open: UK daily rainfall data, v201901, Centre for Environmental Data Analysis, 10.5285/ec54d5e5288a4ebb8c7ad2a1ef6aec42, 2019.

Marsh, T., Cole, G., and Wilby, R.: Major droughts in England and Wales, 1800–2006, Weather, 62, 87-93, 10.1002/wea.67, 2007.

Smith, K.A.; Tanguy, M.; Hannaford, J.; Prudhomme, C. (2018). Historic reconstructions of daily river flow for 303 UK catchments (1891-2015). NERC Environmental Information Data Centre. https://doi.org/10.5285/f710bed1-e564-47bf-b82c-4c2a2fe2810e

Smith, K. A., Barker, L. J., Tanguy, M., Parry, S., Harrigan, S., Legg, T., Prudhomme, C., and Hannaford, J.: A Multi-Objective Ensemble Approach to Hydrological Modelling in the UK: An Application to Historic Drought Reconstruction, Hydrology and Earth System Sciences, 23, 3247-3268, https://doi.org/10.5194/hess-23-3247-2019, 2019.

Spraggs, G., Peaver, L., Jones, P., and Ede, P.: Re-construction of historic drought in the Anglian Region (UK) over the period 1798–2010 and the implications for water resources and drought management, Journal of Hydrology, 526, 231-252, https://doi.org/10.1016/j.jhydrol.2015.01.015, 2015.

Svensson, C., Hannaford, J., and Prosdocimi, I.: Statistical distributions for monthly aggregations of precipitation and streamflow in drought indicator applications, Water Resources Research, 53, 999-1018, 2017.

Historic hydrological droughts 1891-2015: systematic characterisation for a diverse set of catchments across the UK

Lucy J. Barker[1], Jamie Hannaford[1, 2], Simon Parry[1], Katie A. Smith[1], Maliko Tanguy[1], Christel Prudhomme[3, 1, 4]
[1] Centre for Ecology & Hydrology, Wallingford, UK
[2] Irish Climate Analysis and Research UnitS (ICARUS), Maynooth University, Ireland
[3] European Centre for Median-range Weather Forecasts, Reading, UK
[4] Loughborough University, Loughborough, UK
Correspondence to: Lucy J. Barker (lucybar@ceh.ac.uk)

Abstract. Hydrological droughts occur in all climate zones and can have severe impacts on society and the environment. Understanding historical drought occurrence and quantifying severity is crucial for underpinning drought risk assessments and the developing drought management plans. However, hydrometric records are often short and capture only a limited range of variability. The UK is no exception: numerous severe droughts over the past 50 years have been well captured by observations from a dense hydrometric network. However, a lack of long-term observations means that our understanding of drought events in the early 20th century and late 19th century is limited. Here we take advantage of new reconstructed flow series for 1891 to 2015 to identify and characterise historic hydrological droughts for 108 near-natural catchments across the UK using the Standardised Streamflow Index. The identified events are ranked according to four event characteristics (duration, accumulated deficit, mean deficit and maximum intensity), and their severity reviewed in the context of events of the recent past (i.e. the last 50 years). This study represents the first national scale assessment and ranking of hydrological droughts. Whilst known major drought events were identified, we also shed light on events which were regionally important such as those in 1921 and 1984 (which were important in the south-east and north-west of the UK, respectively). Events which have been poorly documented such as those of the 1940s in the post-war years, or the early 1970s (prior to the landmark 1975-1976 event), were found to be important in terms of their spatial coverage and severity. This improved knowledge of historic events can support improved long-term water resources planning approaches. Given the universal importance of historical drought appraisal, our systematic approach to historical drought assessment provides a methodology that could be applied in other settings internationally.

1 Introduction

In all climate zones, droughts are a major natural hazard and can threaten water supplies and trigger severe societal and environmental consequences (e.g. Bachmair et al., 2016a). Proactive drought risk assessment and planning are essential cornerstones of efforts to manage the impacts of droughts in many countries (Wilhite et al., 2000). Such activities rely on an understanding of the likelihood of droughts of a given severity, in addition to information on vulnerability of supply infrastructure, populations, ecosystems etc. The likelihood of drought occurrence is contingent on an understanding of past hydrometeorological variability, which in itself depends on long historical records of observational data (of rainfall, evapotranspiration, river flows, groundwater etc.). While water resources and drought planning efforts have evolved over the last three decades to incorporate climate model-based assessments of future climate variability under anthropogenic warming scenarios (Brown et al., 2015), the inherent uncertainties in these simulations mean that historical records are still of fundamental importance in drought planning – as well as providing the data to corroborate modelling projections and provide a baseline against which future changes can be assessed.

While the UK is a humid country, it has periodically suffered from severe droughts which have caused major water shortages and subsequent impacts (e.g. Marsh et al., 2007). Parts of the UK are water stressed owing to a delicate balance between supply and demand – notably, in some of the drier areas of the south and east where some of the greatest concentrations of population live alongside intensive agriculture and commerce (Environment Agency and Natural Resources Wales, 2013). Consecutive dry winters pose a particular threat in these areas where groundwater makes up a large proportion of public water supply, as was demonstrated in the recent droughts of 2004-2006 and 2010-2012 (e.g. Parry et al., 2016). These reserves are reliant on recharge over the winter months to replenish supplies. In the wetter north and west, droughts may, intuitively, not be regarded as a major issue, but natural catchment storage is limited and even relatively short periods of warm and dry weather can cause significant risks to water supply (as occurred in summer 2018, e.g. Barker et al., 2018a).

Deleted: ,

Deleted: (as occurred in summer 2018, e.g. Barker et al. (2018a))

As with other regions, there remain large uncertainties in hydrological projections for the UK (Watts et al., 2015) but the general expectation of increased evaporative demand under anthropogenic warming is expected to trigger drying, particularly in summer months (Prudhomme et al., 2011). Moreover, greater climatic variability could mean an increase in persistent blocking episodes and multi-year droughts (e.g. Folland et al., 2015), which are the greatest challenges in the most vulnerable areas of south-east England. These factors have led the UK Climate Change Risk Assessment to identify water scarcity as a major risk for the UK (Adaptation Sub-Committee, 2016). Even without climate change impacts, demographic and economic changes are expected to significantly influence future water demands (e.g. Water UK, 2016; National Infrastructure Commission, 2018), and the need to ensure favourable conditions for aquatic ecology places a constraint on future water availability (Environment Agency, 2009).

There is therefore, a pressing need for improved tools for drought risk assessment, the development of which is contingent on a proper quantification of past occurrence of droughts in the UK. Droughts are a complex hazard and it is crucial to quantify and understand not just a peak intensity, but duration and spatial extent, all of which are interdependent and different for individual events (Van Loon et al., 2016). Given the usually large spatial footprint and long timescales of drought, it is also challenging to define drought episodes as self-contained events (and as a result, their onset, termination, seasonality etc.), underlining the importance of consistent, quantitative methods for drought identification.

Knowledge of past droughts is crucial for supply system planning. In the UK, as in many countries, water resources management plans and droughts plans have long relied on a 'drought of record', i.e. using the worst observed historic drought to test the resilience of supply systems (Environment Agency, 2015). More recently, there has been a shift towards stochastic approaches to test the resilience of systems to droughts that are worse than those observed in the recent past (Anderton et al., 2015; Water UK, 2016). These approaches recognise the need to go beyond the envelope of past variability, not just in the context of climate change but given short observational records, wherein it may be expected that 'record breaking' events will occur due to chance alone (as has been described for flooding events, for example: Thompson et al. (2017) and Kjeldsen and Prosdocimi (2018)). However, these stochastic approaches still require benchmarking against historic data, and where longer historic data are available the increased sample size increases the confidence in synthetic events generated using historical training data.

Deleted: Thompson et al. (2017) (for example: Thompson et al., 2017; Kjeldsen and Prosdocimi, 2018))

The occurrence of droughts in recent decades is well understood in the UK, with most events since 1976 having been documented extensively by the National Hydrological Monitoring Programme (http://nrfa.ceh.ac.uk/nhmp). However, our understanding of hydrological drought occurrence is grounded in the period since 1961 when most UK river flow records commenced. Only a handful of hydrometric records extend back to the early 20th century meaning there are few observations on which to base systematic, national scale assessments of drought severity. In a seminal study, Marsh et al. (2007) (see also: Cole and Marsh, 2005) synthesised a range of datasets, to provide an assessment of historic droughts in England and Wales between 1800 and 2006, identifying nine 'major' episodes of which only four are in the well-gauged period of the last five decades. Whilst the study rightly encouraged a longer view, the approach to drought characterisation was qualitative and relied on a small number of long rain gauge and groundwater records, as well as documentary sources.

Deleted: 1960

The British Isles is blessed with plenty of long rainfall series. This has allowed quantitative identification of meteorological droughts back to the 17th century, e.g. Todd et al. (2013). Similarly, in Ireland, Noone et al. (2017) developed a drought catalogue back to the 18th century using long rainfall records. But in the context of drought, it is not sufficient to quantify meteorological deficits alone. As some of the most severe drought impacts on society and the environment result from hydrological drought (i.e. deficits in river flows and groundwater levels), and given that the propagation from meteorological to hydrological drought is highly non-linear (e.g. Barker et al., 2016), assessments based solely on meteorology can be misleading (Van Lanen et al., 2013).

Given the lack of long river flow records, such long rainfall records can be used to reconstructed river flow data to extend our knowledge of past variability. The most notable existing example is the work of the Climate Research Unit which has allowed a window into past droughts back to 1865 (Jones, 1984; Jones and Lister, 1998; Jones et al., 2006). However these studies reconstructed river flows for just 15 catchments across England and Wales, were based on empirical rainfall-runoff relationships and made a number of simplifying assumptions such as the use of constant potential evapotranspiration through time (which plays an important role in discharge generating processes, particularly in the mid-latitudes). There have been some efforts to reconstruct hydrological droughts on a regional scale, the results of which have been run through water supply system models: e.g. for East Anglia (Spraggs et al., 2015) and the Midlands (Lennard et al., 2016). At the national scale, an assessment of past hydrological droughts was recently undertaken by Rudd et al. (2017) which benchmarked a national gridded hydrological model against the droughts identified in Marsh et al. (2007) aggregated over river basin regions, but did not assess the relative severity or spatio-temporal dynamics of historical episodes. Internationally, although many studies have identified and described historic periods of meteorological drought (e.g. Noone et al., 2017; Pfister et al., 2006; Spinoni et al., 2015), there have been few efforts to reconstruct historic hydrological droughts at the broad, national scale. An exception is Caillouet et al. (2017) which used rainfall-runoff model based reconstructions for 662 catchments across France.

The aim of this study is to provide the first comprehensive assessment of historic hydrological droughts at the UK scale; providing an up-to-date, objective and quantitative assessment of the severity of major droughts, extending the work of Marsh et al. (2007) (hereafter, for brevity referred to as MCW2007). However, unlike MCW2007, this study focuses on hydrological, specifically river flow, drought. River flow integrates upstream processes combining the effects of climate and the physical catchment properties and is therefore good indicator of water availability. This study is part of ‘Historic Droughts’ (historicdroughts.ceh.ac.uk), a multidisciplinary project, which aims to understand past drought from a range of perspectives, with a hydrometeorological assessment at its foundation.

This paper:

- Presents timelines of historic reconstructed droughts for over 100 near-natural catchments,
- Characterises the severity of these past drought events – in terms of duration, accumulated deficit, mean deficit and maximum intensity,
- Ranks historic droughts according to these drought event characteristics and assesses how relative rankings vary by geography and the ranked drought characteristic, and
- Provides a fuller description of the evolution and characteristics of major, nationally important droughts from the pre-1961 period.

2 Data and Methods

2.1 Data

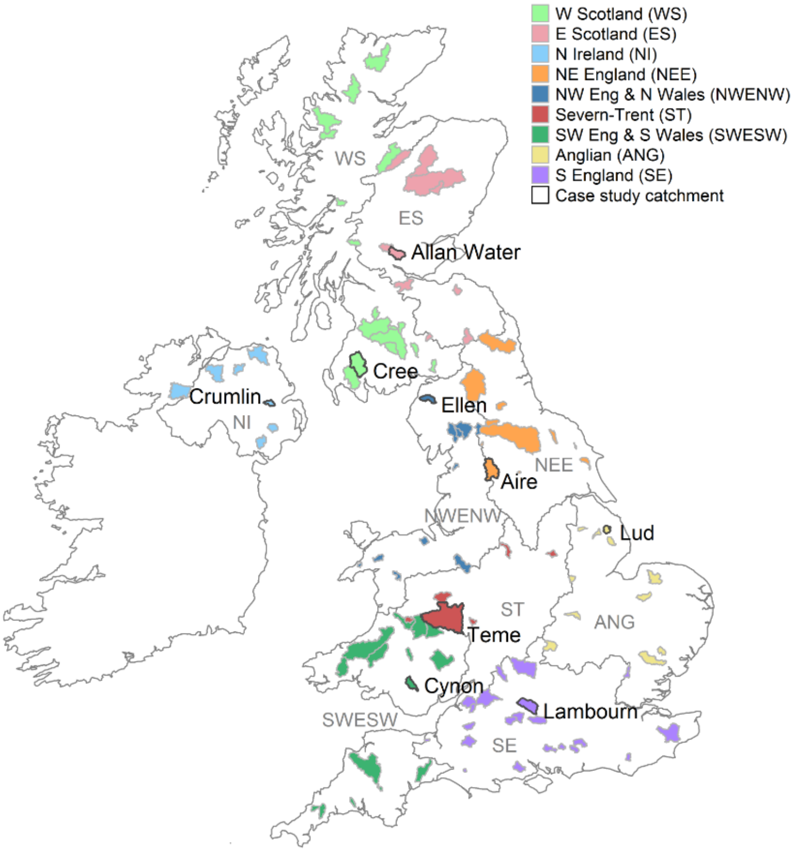


Figure 1 The 108 low flow Benchmark Network (LFBN) catchments used in this study which are included in the river flow reconstructions of Smith et al. (2018), highlighting nine selected case study catchments. Catchments are coloured by the hydroclimate regions of Harrigan et al. (2018). See Table S1 for a list of catchments and basic catchment information.

This study makes use of a comprehensive new dataset of reconstructed river flows from 1891 to 2015 for 303 diverse catchments across the UK (Smith et al., 2018). These reconstructed daily river flows were derived from a hydrological model which was driven by newly rescued and digitised meteorological data from UK observing stations held in the paper records of the National Meteorological Archives. These rainfall data are described in Hollis et al. (2019) and available in: Met Office (2018) and Met Office (2019). The hydrological model required daily rainfall and potential evapotranspiration (PET) as inputs, the latter of which was calculated using newly recovered temperature data (Tanguy et al., 2018). The hydrological model employed was the GR4J daily lumped rainfall-runoff model (Perrin et al., 2003), implemented using the 'airGR' R package version 1.0.2 (Coron et al., 2017) as described by Smith et al.

Deleted: ,

Deleted: Hollis et al. (2019)Hollis et al. ((Legg and McCarthy, in preparation)Hollis et al. (submitted)

Deleted: the

(2018) and Smith et al. (2019). GR4J has previously been used for low flow reconstructions in France (Caillouet et al., 2017) and has demonstrated good performance in a diverse range of catchments in the UK (Harrigan et al., 2018). GR4J was calibrated using a Latin Hypercube Sampling (LHS) technique to ensure each parameter was sampled in an efficient manner, producing 500,000 model parameter sets for each catchment. The 500,000 model results were then analysed and ranked using six evaluation metrics (the Nash-Sutcliffe efficiency, absolute percent bias, mean absolute percent error, Nash-Sutcliffe efficiency on log flows, absolute percent error in Q95, and the absolute percent error in the mean annual minimum on a 30 day accumulation period) which assessed model performance across the flow regime but included drought and low flow specific metrics (Smith et al., 2019). From the 500,000 model runs for each catchment, Smith et al. (2018) identified the best performing model run – referred to as LHS1. Smith et al. (2019) also assessed the model parameter uncertainty for the top 500 model runs, but here, the LHS1 dataset was used to investigate historic hydrological droughts. LHS1 was selected due to the computational demand of the distribution fitting associated with the derivation of the Standardised Streamflow Index (see below).

Deleted: Smith et al 2019

In this study, we used a subset of the 303 catchments modelled by Smith et al. (2018), i.e. stations from the National River Flow Archive's (NRFA) UK Benchmark Network (Harrigan et al., 2017), in particular those stations suitable for low flows, hereafter referred to as the Low Flow Benchmark Network (LFBN). The NRFA's UK Benchmark Network provides a network of gauging stations monitoring near-natural catchments, with limited net artificial influences on flows (Harrigan et al., 2017). The use of near-natural catchments enables the hydro-climatic signal to be separated from confounding impacts (such as human modifications to catchments or influences on flows); especially vital given that human impacts are not explicitly accounted for in the modelling approach used (Smith et al., 2019).

Deleted: low

Deleted: flow

The 303 UK catchments reconstructed by Smith et al. (2018), which include the LFBN, performed well in model validation steps which included assessing model performance for a range of metrics which summarised how well the model reproduced discharge across the flow regime, as well as testing the skill of the model for low flows and drought specifically (Smith et al., 2019). Here, where model evaluation criteria fell below the middle of the three model performance thresholds defined by Smith et al. (2019), catchments were removed. The LFBN generally performed well, and only seven catchments were excluded from the full LFBN (115 catchments), resulting in 108 catchments appropriate for this study (shown in Figure 1). A list of the 108 LFBN catchments used in this study is provided in Table S1, and the model performance metrics for the LHS1 runs from Smith et al. (2018) for the LFBN catchments are shown in Figure S1. To provide some geographic context to figures, hydroclimate regions of the UK described in Harrigan et al. (2018) (shown in Figure 1) were used in the description of the results. A set of nine case study catchments was chosen from the LFBN (one per hydroclimate region, shown in Figure 1) representing a range of catchment types and geographies across the UK, enabling catchment-scale

Deleted: highest

Deleted: s

Deleted: of the model performance metrics for the LFBN

Deleted: Figure 1

Deleted: and

results to be shown. The following case study catchments were selected (the hydroclimate region is given in brackets): Cree (WS), Allan Water (ES), Crumlin (NI), Aire (NEE), Ellen (NWENW), Teme (ST), Cynon (SWESW), Lud (ANG) and Lambourn (SE).

2.2 Drought indicators

The Standardised Streamflow Index (SSI; Vicente-Serrano et al., 2011) was calculated for each LFBN catchment using reconstructed flow data (Smith et al., 2018) for the period 1891-2015 (Barker et al., 2018b). The standardisation of the reconstructed streamflow allowed consistent comparison over both time and space and provided a measure of drought severity – crucial characteristics for a quantitative and rigorous assessment of drought event characteristics over time and space.

Daily mean river flow reconstructions were aggregated to mean monthly flows for each catchment in the LFBN. The SSI was then calculated for 3 and 12 end-month accumulation periods, where for example the December SSI-3 represents flow deficits from October to December, whilst the December SSI-12 represents deficits from January to December. The 12-month accumulation period (SSI-12) gives a summary of long-term annual (multi-season) deficits likely to have greater impact on water resources (whether groundwater or multi-season reservoirs). The 3-month accumulation period (SSI-3) characterises short-term seasonal river flow deficits and impacts on smaller, single season reservoirs. For practical applications, the accumulation period most appropriate for a given water resources system, or a particular type of drought impact, varies around the country (Bachmair et al., 2016b). In general, longer periods are more important in the south and east (including durations even longer than those used here, e.g. 24- or 36-months) and shorter periods in western areas (e.g. Barker et al., 2016; Folland et al., 2015; Marsh et al., 2007). However, due to substantial spatial variation two contrasting accumulation periods are used for all sites.

Deleted: (Barker et al., 2016)

Deleted: (Barker et al., 2016)

The SSI was calculated using the Tweedie distribution, which has been found to have the best fit for observed river flow data for UK Benchmark catchments (Svensson et al., 2017), the majority of which overlap with the 108 LFBN catchments used in this study. The Tweedie distribution was recommended in the UK by Svensson et al. (2017) following rigorous testing of 12 distributions, with special attention paid to the tails of the distribution. The Tweedie has the advantages of being a flexible three parameter distribution that has a lower bound at zero. Due to the uncertainties associated with extreme SSI values (e.g. Stagge et al., 2015), values were limited to the range -5 to 5.

Although the daily river flow reconstructions had no missing data, there were five individual months to which a Tweedie distribution could not be fitted and so did not have an SSI value. All five months of missing data appear in the SSI-3 series for four catchments and equate to 0.0015% of available data for the 108 catchments and two accumulation periods for the period 1891-2015 (see Table S2 for details). Four of these missing data points occurred during periods of positive SSI (i.e. above normal flows) and

Deleted: S1

so did not affect the identification of drought events (see Section 2.3). The last missing data point occurred in December 1921 for the Great Stour at Horton (South East England); and was infilled with the SSI value of preceding and subsequent months (both -5).

2.3 Drought event extraction and characteristics

Drought events were defined as months with consecutively negative SSI values with at least one month in the negative series reaching a threshold of -1.5 (equating to ‘severe’ drought; Barker et al., 2016). For each extracted event, the following characteristics were calculated (after Noone et al., 2017, see Figure 2):

- Duration (number of months),
- Accumulated deficit (sum of SSI values across the event duration),
- Mean deficit (accumulated deficit divided by duration), and
- Maximum intensity (the minimum SSI value during the event).

Due to the seasonal focus of the study, events with a duration of less than three months (i.e. one or two months) were removed. As the accumulated deficit and mean deficit were derived from the SSI, they represent relative deficits, not absolute flow deficits (for example, as mm or a volume)

Deleted: are

The extracted events were ranked by each event characteristic (i.e. duration, accumulated deficit, mean deficit and maximum intensity) and the top 10 events for each characteristic and accumulation period were identified. When ranking by duration, tied events were also sorted by the accumulated deficit so the longest events with the lowest (i.e. most negative) accumulated deficit ranked highest.

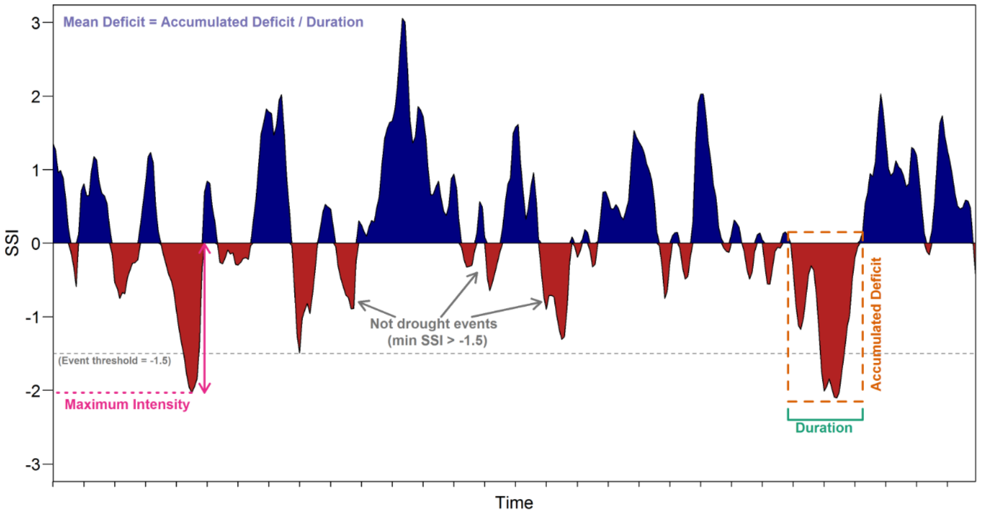
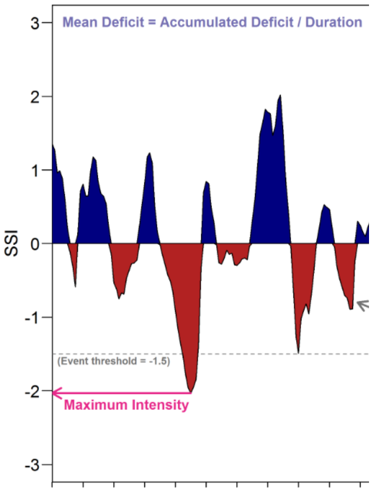


Figure 2 Conceptual diagram illustrating drought event identification and characteristics (N.B. x-axis ticks represent years, but SSI data are on a monthly time-step).

Deleted:



All extracted drought events were compared to events identified as ‘major’ droughts in England and Wales by MCW2007, or documented as such by the National Hydrological Monitoring Programme and UK Met Office (2004-2006 and 2010-2012 (e.g. Marsh (2007); and Kendon et al. (2013), respectively). Using information from their relevant publication, the start and end months were identified for each event (listed in Table 1). Where the extracted events (from the reconstructed SSI series) overlapped with the major event periods given in Table 1, the extracted event was assigned to the corresponding ‘major’ drought. Extracted events which did not overlap with these known drought periods, were classified as ‘other events’ and were assessed in more detail.

Deleted: , respectively)

Deleted: they

Table 1 Major droughts and their start/end dates as identified by MCW2007, asterisk denotes events not listed by MCW2007, but were significant events reported by the National Hydrological Monitoring Programme.

Formatted Table

‘Major’ Droughts	Start month	End month
(‘The Long Drought’ period) 1890-1910	1890-Jan	1910-Dec
1921-1922	1920-Sep	1922-Mar
1933-1934	1932-Sep	1934-Nov
1959	1959-Feb	1959-Nov
1976	1975-May	1976-Aug
1990-1992	1990-Mar	1992-Aug
1995-1997	1995-Mar	1997-Aug
*2004-2006	2004-Feb	2006-Oct

‘Major’ Droughts	Start month	End month
*2010-2012	2010-Jan	2012-Mar

3 Results

3.1 Timelines of historic reconstructed drought

Figure 4 provides a national scale assessment of drought occurrence, showing the SSI-12 in the form of a heatmap, with catchments orientated roughly from north to south. Spatially coherent phases of below normal flows (referred to as low flows throughout this section) can be identified in Figure 4, with particularly intense periods of low flows in the mid-1930s and 1976 when there were extreme deficits across the UK. Periods of regionally low flows occurred in Northern Ireland in the mid-1890s, the early 1920s and the 2010-2012 event in southern England, and 1995-1997 in northern England. The period from 1890 to 1910 (referred to by MCW2007 as the ‘Long Drought’) was a prolonged period of low flows punctuated by periods without flow deficits – e.g. 1903-1905 where above normal flows were recorded across the country.

In general it appears that more intense low flows occurred in the pre-observation period (i.e. before 1961), whilst the 1980-2015 period included more above normal flow episodes in northern regions (particularly WS) indicated by the white spaces in Figure 4. Across the UK hardly any extreme low flows occurred in the 1980s over the 12-month accumulation period (Figure 4), with the decade generally showing mild drought conditions or above normal flows.

At the shorter three month accumulation period, there was more variability of SSI in both time and space (Figure S2), although there were some similarities to the SSI-12 (Figure 4). The 1920s (also identified in SSI-12) show intense low flow events in southern England. Severe and extreme low flows can be seen in the pre-observation period, and fewer events occurred during the 1980s to early 2000s (except in WS). Although slightly obscured by the very fine-scale variations shown in Figure S2, some spatial coherency emerges for SSI-3 (Figure S2). For example, the 1976 drought, intense in SE and ANG regions, extends northwards and is apparent across the UK. The events of the mid-1930s occur across the UK with the lowest flows in Northern Ireland. The 1995-1996 drought occurs across England and Wales, and to some extent in Scotland – whilst it highlighted longer-term deficits across northern England for SSI-12. At the shorter three month accumulation period, the distinction between Southern England and Anglian regions and the rest of the country is more apparent than at the 12 month accumulation period, with more space-time consistency in SSI values in the south east of England.

Formatted Table

Deleted: broadly

Deleted: western Scotland

Deleted: S1

Deleted: western Scotland

Deleted: S1

Deleted: 1

Deleted: Southern England

Deleted: Anglian

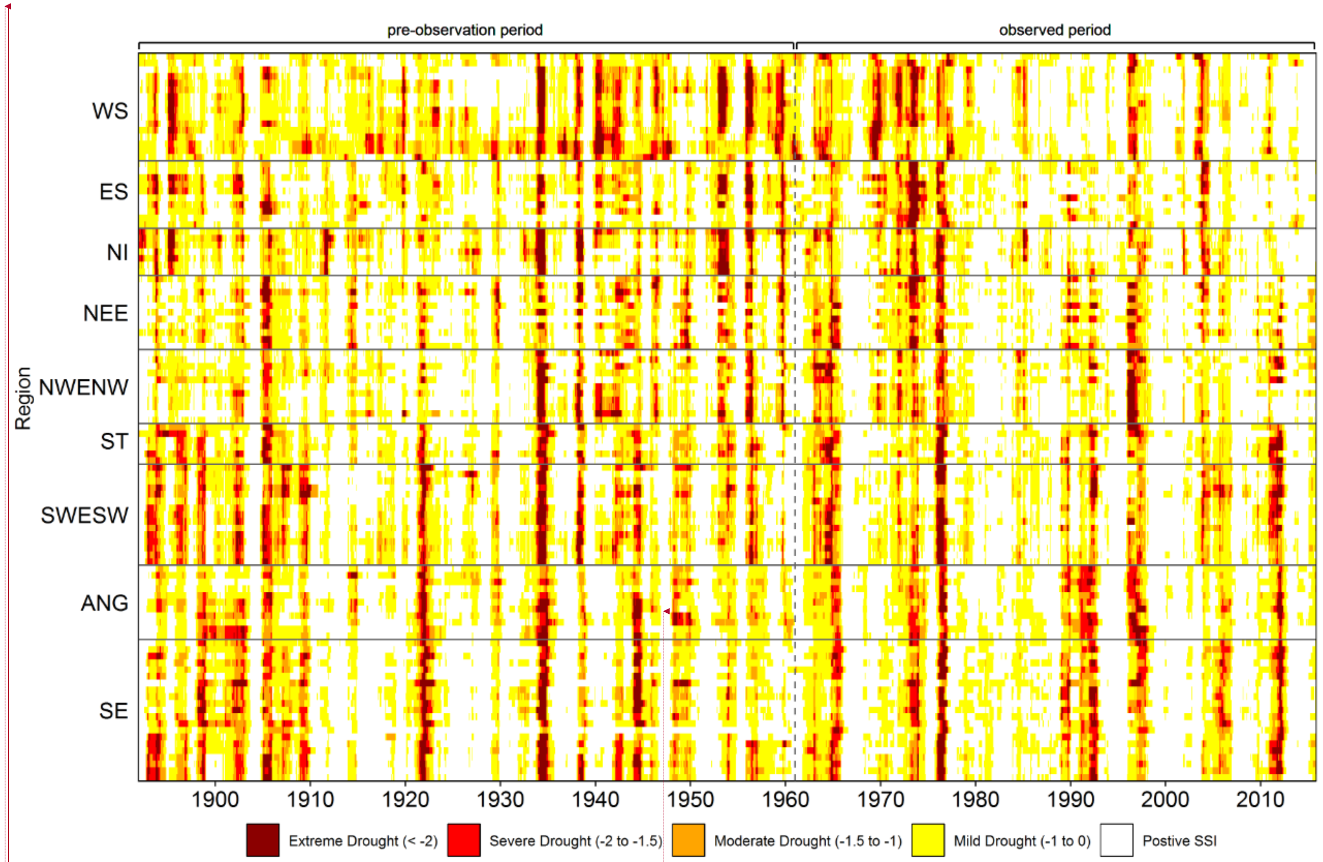
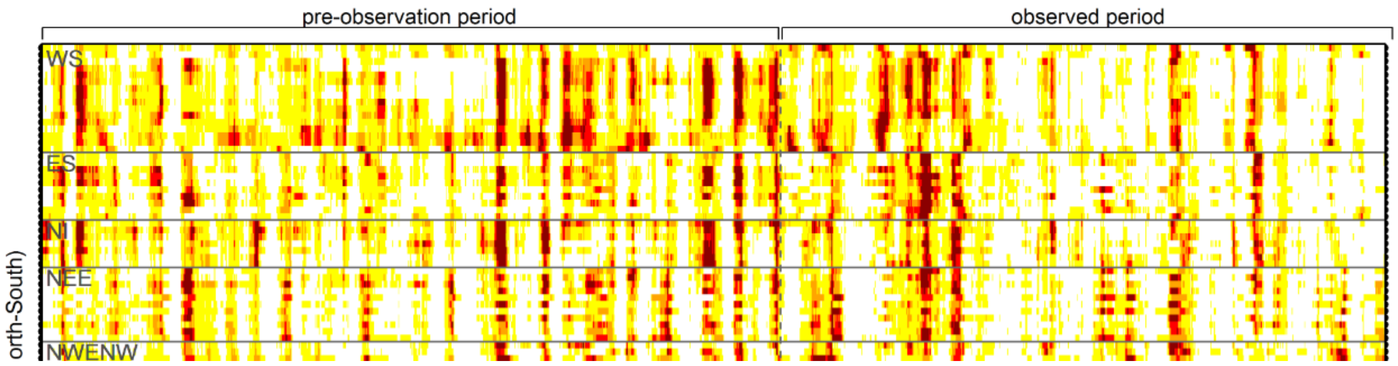


Figure 3 Heatmap of SSI-12 for LFBN catchments (arranged roughly from north to south on the y-axis, with one row per catchment and regions marked for clarity) from 1891 to 2015.

-1)

Deleted:



3.2 Characterising the severity of past events

The extracted drought events and their characteristics for the nine case study catchments are shown in Figure 5 for SSI-12 and Figure S3 for SSI-3. The identified events tend to be longer and less frequent in more southerly catchments regardless of the SSI accumulation period. Events with a lower negative maximum intensity (i.e. more severe) tend to occur before 1960, particularly in more northerly catchments; a similar pattern can be seen for mean deficit. Maximum intensity and mean deficit seem unaffected by duration, with severe events occurring over the range of durations plotted. On the Cree, Allan Water and Lud events were clustered in time (e.g. in the 1930s-1950s, before the 1977 and after 1962, respectively), elsewhere events were more evenly spaced through time. Shorter events tend to have occurred in the last 30 years on the Crumlin and in Scotland, whilst SSI-3 events were longer after the 1970s on the Lambourn.

Deleted: 2

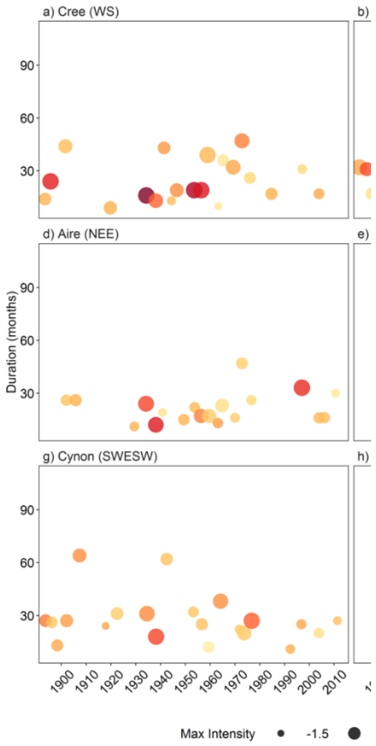
Deleted: For both accumulation periods,

Deleted: lower

Deleted: (i.e. more severe)

Deleted: in the pre-observation period, a similar pattern can be seen for mean deficit

Figure 5 Extracted events from SSI-12 and their characteristics for the nine case study catchments, plotted at the midpoint of the event. The size of each point is proportional to the maximum intensity and the colour indicates the mean deficit.



Deleted:

3.3 Ranking historic drought events

The longest SSI-12 events varied by location (Figure 5a), but the longest events mostly occurred before 1990 and were clustered between 1940 and 1980.The SSI-12 events of the early to mid-1970s were, for the most part, the longest in northern England, north Wales, Northern Ireland and Scotland (Figure 6a). Events in the 1960s ranked highly across the UK (with the exception of Scotland), the 1970s in the north of the UK and the 1900s in the south of England. Many of the 10 longest events occurred during the 'Long Drought' period from the 1890s to 1910s but in many cases these were not the top ranking (i.e. most severe) events.

The event rankings for accumulated deficit were similar to those for duration (Figure 6a and Figure 6b) as longer events are likely to have greater accumulated deficit. When the accumulated deficit is divided by the duration to produce the mean deficit however, a different picture emerges (Figure 6c). The 1975-1976 event stands out as being highly ranked in terms of mean deficit in southern England and Wales. Events in the mid-1930s rank in the top three across the country. Other severe drought events occurred in the 1950s across northern Britain, in the late 1990s in northern England and Wales as well as the mid-2000s in some catchments in ES, whilst the rank of events in the 1900s and 1960s decreases when looking at mean deficit compared accumulated severity. Several events occurring during the 'Long Drought' period (1890-1910) ranked in the top 10 when considering mean deficit, especially in southern England. The 1920s in south-east England and the 1930s, nationally, stand out dramatically when events are ranked by the maximum intensity (i.e. the lowest monthly SSI value in the event; Figure 6d). This drought characteristic, more than the others shows a propensity to more severe events in the earlier part of the reconstructed series than other characteristics.

Formatted: Space After: 0 pt, Keep with next

Formatted: Font: 11 pt

Deleted:

Formatted: Font: 11 pt

Formatted: Font: 11 pt

Formatted: Font: 11 pt

Deleted: eastern Scotland

Deleted: 5d

Deleted: record

Formatted: Font: 11 pt, Do not check spelling or grammar

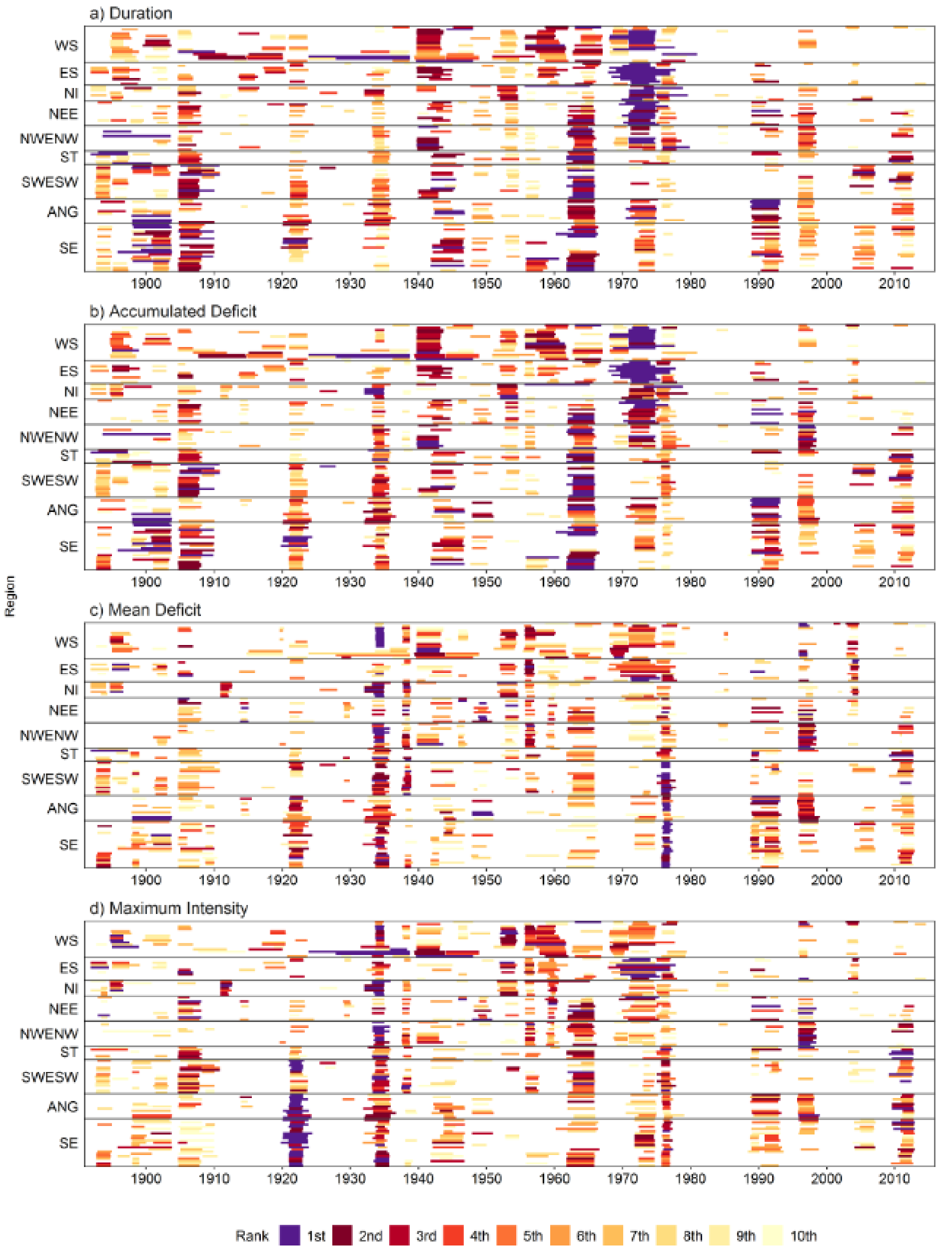
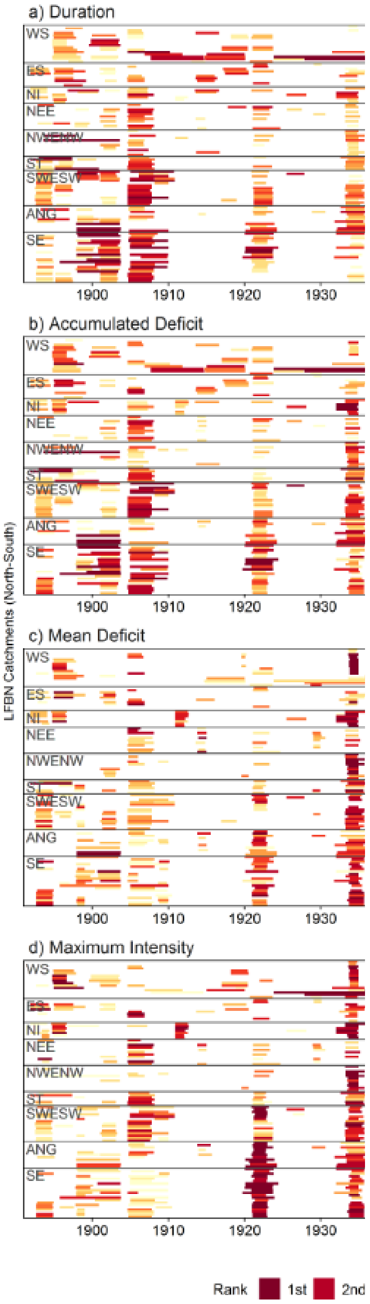


Figure 6 Top 10 extracted events from SSI-12 using a threshold of -1.5 for each drought event characteristic. Catchments are arranged roughly from north to south on the y-axis with each row representing a catchment and regions marked for clarity. Bars represent the top 10 events and are coloured according to the event rank; darker shades represent higher ranking (i.e. more severe) events.



Deleted:

Formatted: Keep with next

Formatted: Font: 11 pt

Formatted: Font: 11 pt

Formatted: Font: 11 pt

Formatted: Normal

For SSI-3, more recent events such as those in the 1990s, 2004-2006 and 2010-2012 rank highly in Anglian and South-East England regions. The drought of 1975-1976 is ranked highly in terms of duration in northern and western regions, but at this shorter accumulation period ranks lower in south-east regions (Figure S4a). When accumulated deficit is considered (Figure S4b), the 1920s ranks in the top half of the rankings across regions of southern England and Wales, whilst the 1930s is coherently ranked in the top 10 across the country (and was particularly highly ranked in Northern Ireland and the south of the UK). The drought of 1995-1997 is highly ranked in the regions of northern England and ANG, with events throughout the 1990s being particularly severe in ANG. When ranked by mean deficit, events such as the early 1920s rank highly in south-eastern regions, and the 1929 drought ranks highly (and was ranked top in some catchments in ES and NEE; Figure S4c). In contrast to the duration rankings, catchments in South-East England and Anglian regions ranked highly (and top in many) for 1975-1976, whilst at this shorter accumulation period, the summer drought of 1984 appears in the top half of the rankings, particularly in western regions. The late 1920s (1929) also ranks highly in more northerly and westerly regions for the maximum intensity while the early 1920s ranks particularly highly in ANG and SE regions as does 1975-1976 (Figure S4d).

Figure 7 shows the LFBN catchments where the top ranking SSI-12 events for each event characteristic correspond to the major drought events listed in Table 1. Across England and Wales, the 'Long Drought' period (1890-1910) was the longest event with the largest accumulated deficits events, but the most severe event according to mean deficit and maximum intensity in the north of the UK. In contrast, the 1975-1976 event was worse in terms of mean deficit in southern England and Wales, and amongst the longest with the largest accumulated deficit in northern regions. The events of 1920-1922 and 1933-1934 were amongst the worse in terms of maximum intensity in the south-east and west of the UK, respectively. In the north-east coast, the 1990-1992 was overall the worse drought, whilst it was 1995-1996 in central northern England. The 2010-2012 event had the highest maximum intensity in the Welsh borders and some groundwater dominated catchments in the south-east of England. The 1959 and 2004 events were generally not marked as the highest ranking events for any of the characteristics, except in a handful of catchments – at most five individual catchments during the 1959 event for a range of characteristics, and for only three catchments for the 2004 event.

Deleted: **Figure 5 Top 10 extracted events from SSI-12 using a threshold of -1.5 for each drought event characteristic. Catchments are arranged roughly north to south on the y-axis with each row representing a catchment; bars represent the top 10 events and are coloured according to the event rank. Darker shades represent higher ranking (i.e. more severe) events.¶**

Formatted: Font: 12 pt

Deleted: S3a

Deleted: S3b

Deleted: East Anglia

Deleted: the latter being particularly severe for 1990s

Deleted: as well

Deleted: eastern Scotland

Deleted: north-east England

Deleted: 3

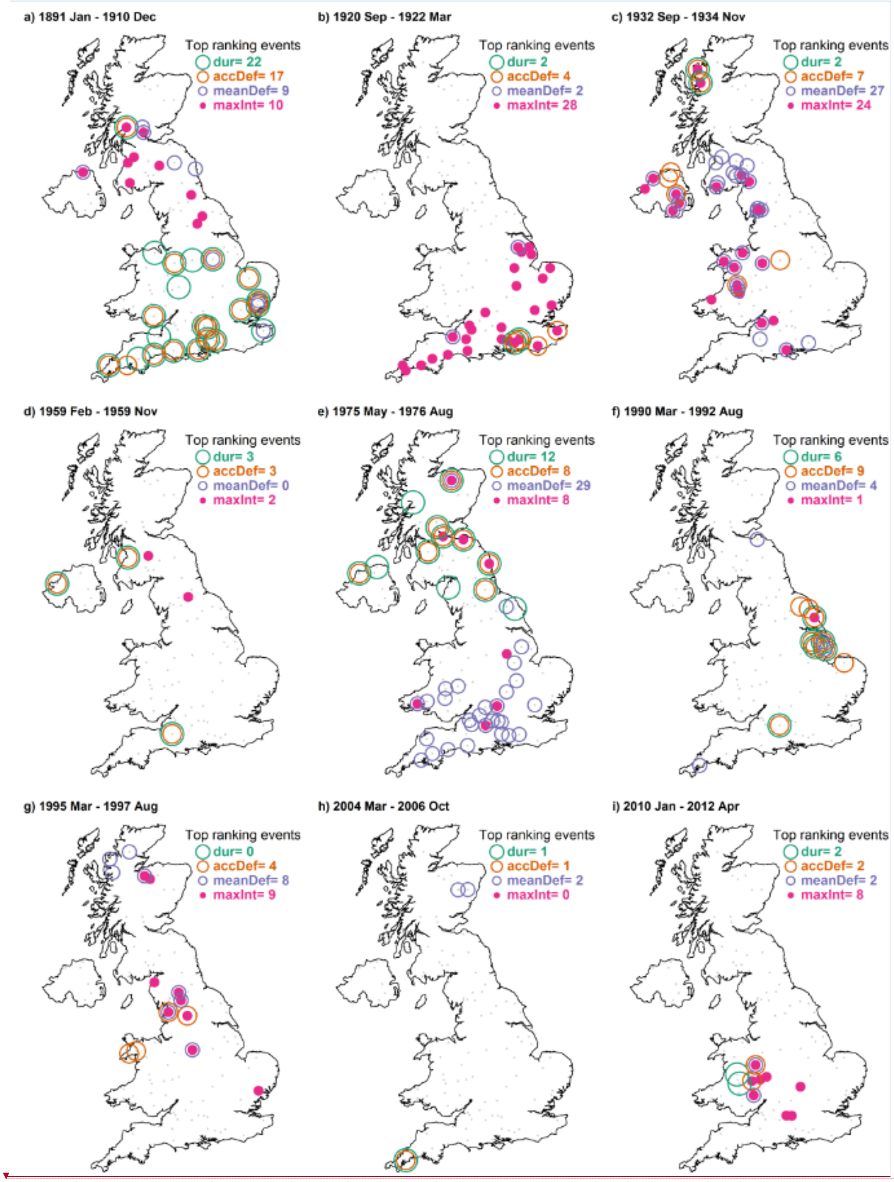
Deleted: Anglian

Deleted: South-East England

Deleted: 3

Deleted: l

Deleted: d



Deleted:

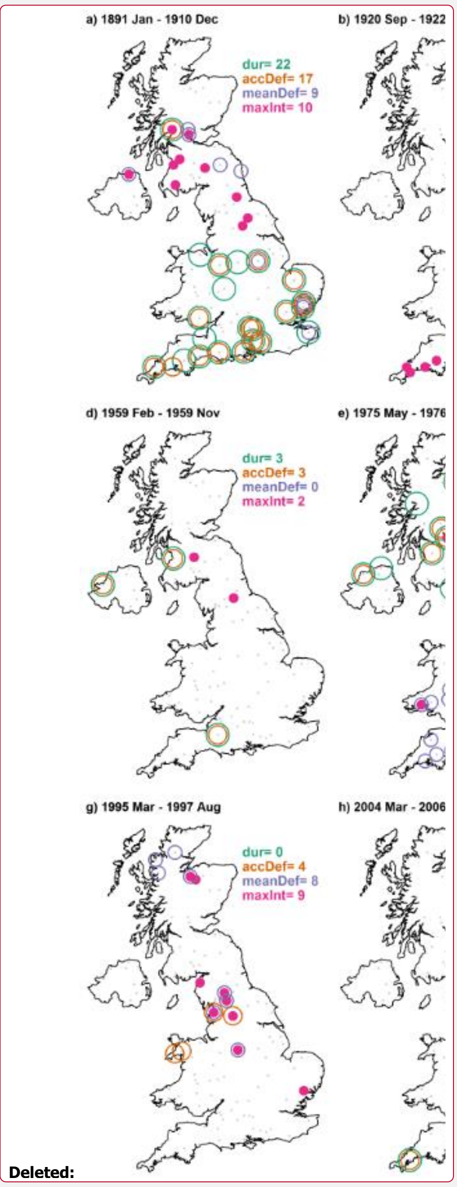
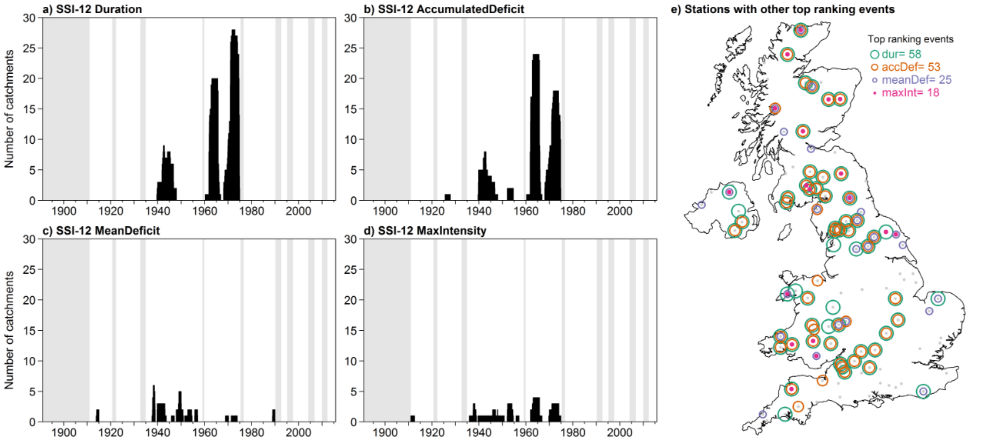


Figure 7 Location and number of LFBN catchments where the top ranking SSI-12 event corresponds to major events (Table 1) for duration (dur), accumulated deficit (accDef), mean deficit (meanDef) and maximum intensity (maxInt). Each of the nine maps represents one of the major drought events listed in Table 1. Each point on the maps represents the location of the 108 LFBN catchments. Points are coloured pink where the particular event was ranked most severe according to maximum intensity for that catchment. Similarly, points are circled in purple, orange and turquoise to indicate catchments where the particular event was ranked most severe in terms of mean deficit, accumulated deficit and duration, respectively. The

numbers in the top right of each map show the number of catchments ranked as most severe for each characteristic for that particular event.



Deleted:

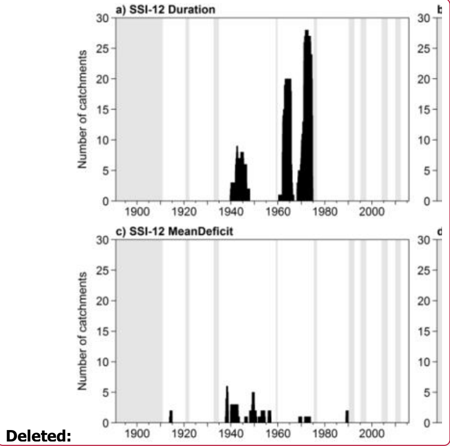


Figure 8 Months when SSI-12 top ranked events occurred outside of the major events (shaded in grey) for the LFBN catchments and each event characteristic (a-d), and e) the location and number of catchments with other top ranking events for each event characteristic. Points are coloured as described in the caption for Figure 6.

Figure 8a-d shows the months when the top ranking SSI-12 event did not correspond to the major events for each event characteristic. The known major drought events exclude top ranking events in the 1940s, 1960s and early 1970s (before the 1975-1976 event) across the four drought characteristics. Figure 8e shows the location of the catchments where the top ranking events occurred outside of the major events, although they occur across the UK, most of these missed events occurred in catchments outside of the south and east of England. A similar spatial pattern can be seen for the top ranking SSI-3 other events (Figure S6e), with a focus in northern and western areas. In contrast to SSI-12, more of the SSI-3 duration and accumulated deficit top ranking events were captured than mean deficit and maximum intensity (around half of which were not captured by the major events). The events not captured by the major events for SSI-3 occurred in similar periods as for SSI-12 (i.e. the 1940s, 1960s and early 1970s), with the addition of the late 1920s, late 1930s and 1984.

Deleted: S5e

For both SSI-3 and SSI-12, the period 1980-2015 appears to be well captured by the major events of Table 1 (see Figure 8 and Figure S6). Figure 9 shows three ‘other’ drought event periods for SSI-12 identified in Figure 8, with top ranking events spread over Great Britain for the 1940s, 1960s and early 1970s. In the 1960s (1960-1966), events were of a longer duration and higher accumulated deficit whilst there were only 4 catchments with top ranking events for maximum intensity and none for mean deficit. Catchments with top ranking events occurring in the 1968-1975 period were focussed in northern parts of the UK with

Deleted: S5

Deleted: and Figure 7

top ranking duration accumulated deficit events spread across Scotland, Northern Ireland and northern England.

For SSI-3, the 1968-1975 period was important for the most severe events according to duration and accumulated deficit in Scotland (Figure S7). Some catchments had top ranking events for more than one characteristic in this period in Scotland, with just four catchments registering top ranking events (for duration and mean deficit) in England and Wales. Other events were ranked most severe in some catchments and event characteristics (Figure S7); 1928-1929 ranked first for mean deficit and maximum intensity across Scotland and northern England. The drought of the early 1950s ranks first across all four event characteristics in Northern Ireland, whilst the 1984 event ranked top for mean deficit in 16 catchments in the west of Great Britain.

Deleted: S6

Deleted: S6

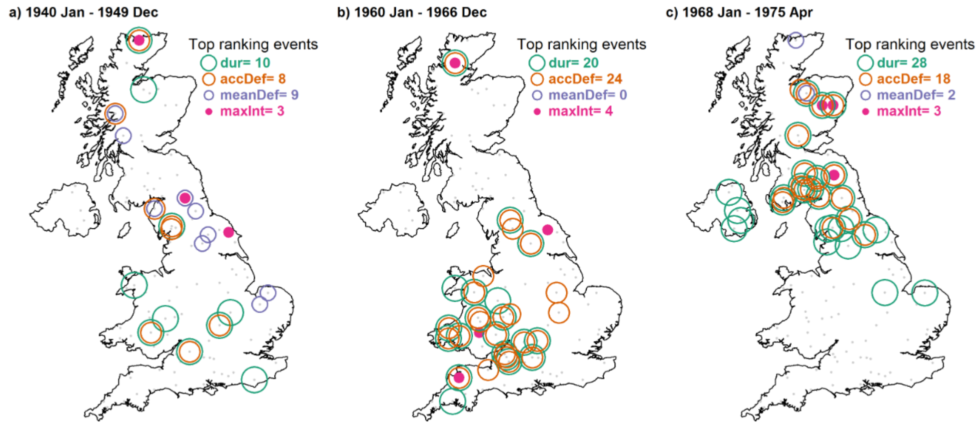
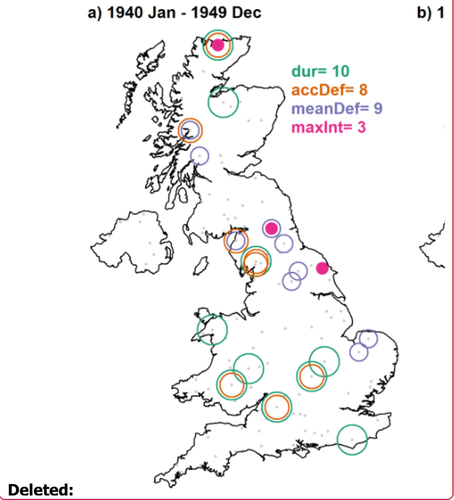


Figure 9 Location and number of LFBN catchments where the top ranking SSI-12 events for each event characteristic occur in periods outside of the major drought events: a) 1940-1949, b) 1960-1966 and c) 1968-1975. Points are coloured as described in the caption for Figure 6.



Deleted:

Finally we consider the rank of all extracted events for SSI-12 for the major events and ‘other’ identified events for each event characteristic (Figure 10). By assessing the rank of all the identified events corresponding to the major events (Table 1) and other identified events (Figure 9), the relative severity of the events can be compared. By placing the top 10 ranks in context, we can see that for some events, the majority of the extracted events fell within the top 10, such as 1995 for duration; 1933 and 1975 for accumulated deficit and mean deficit; and 1920, 1959 and 2010 for maximum intensity. This implies that events such as these were consistently more severe than events with a wider range of ranks or have generally have lower ranks such as 1891-1910 or the 1940s. The median rank of 2004 was outside of the top 10 events across all characteristics, as was 1959 for duration and accumulated deficit, and 1891 for mean deficit and maximum intensity, suggesting that although in some catchments these events were most severe, they were not regularly ranked highly and so were less severe at the national scale. Most of the

Deleted: 9

Deleted: 0

Deleted: r

major and other events identified from the SSI-3 rank outside of the top 10 (Figure S8), with the exceptions of 1933 for accumulated deficit where the 25-75th percentile of events fall within the top 10. This may be a result of the higher number of shorter events extracted from the SSI-3 series. In some cases, the median rank of events falls within the top 10, such as 1933 and 1975 for duration, 1975 for accumulated deficit and 1920 and 1933 for maximum intensity, suggetsing these events were more important a the seasonal scale (SSI-3).

Deleted: S7

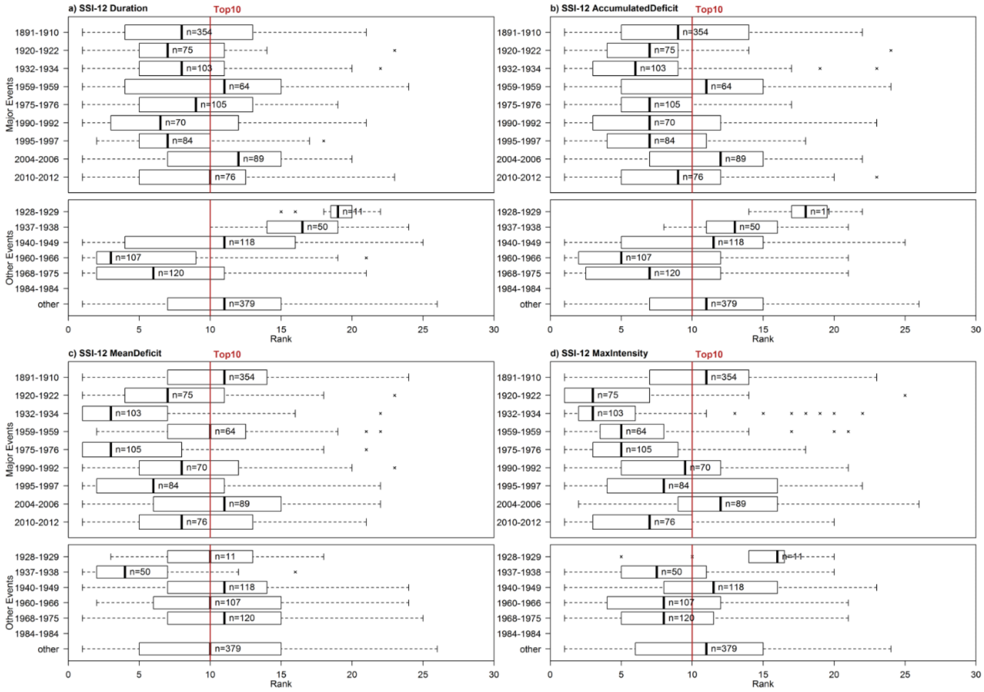


Figure 10 Boxplots showing the ranks of all SSI-12 extracted events where they overlap with the major drought events (top panel for each event characteristic) and identified 'other' events (bottom panel for each event characteristic). Within each box, *n* refers to the total number of events (across the LFBN) identified that occurred within this period. As multiple events can occur within each given period in individual catchments, it is possible for the value of *n* to be greater than the number of catchments (i.e. 108).

3.4 Evolution and characteristics of major pre-1961 events

While previous work and the above analysis has identified the importance of events in the pre-observation period, their hydrological characteristics have not been fully described at the national scale. The flow reconstructions and derived SSI used here allow a more detailed view of the space-time dynamics of these events comparable with those available for events in the gauged era. Figure 11 shows the SSI for the four earliest events identified in this study prior to 1961: the 'Long Drought' period (1891-1910); 1921-1922; 1933-1934; and the 1940s. These events are discussed in more detail in the section below in terms of both SSI-12 and SSI-3; where results pertain to one accumulation period, it has been specified, and otherwise results relate to both accumulation periods.

The 'Long Drought' period (1890-1910)

The 20 year period 1890-1910 (the 'Long Drought') showed periods of low flows across much of the country. For SSI-12, there was often spatial coherency in conditions across southern England and Wales, reducing further north (Figure 11), whilst for SSI-3 (Figure S9), only certain periods show national scale coherency in conditions (such as early 1892, autumn 1892 and 1903-1905). In general however, extreme and severe flow deficits did not occur simultaneously across all regions, e.g. 1895 saw extreme flow deficits across Scotland and Northern Ireland, mild drought in northern England and higher than average flows in the rest of England. With the exception of 1903-1905, northern England was impacted by extreme deficits, whilst several periods of extreme flow deficits occurred in the rest of England throughout this period. More episodes of severe and extreme deficits can be seen at the seasonal scale using SSI-3 throughout the 'Long Drought' period than for SSI-12.

Deleted: s

Deleted: 8

Deleted: were seen

1921-1922

The drought of the 1920s was mostly focussed in England and south Wales with severe flow deficits beginning in summer 1921 across southern England for SSI-12 (Figure 11). However, for SSI-3 1920 ended with severe-extreme flow deficits in WS, but the principal period of deficits started across England (with the exception of NWENW) and Northern Ireland in spring 1921. The event continued for a single season in Northern Ireland and NEE, and until winter 1922 in southern England and Wales (Figure S9). The most extreme flow deficits were experienced over the autumn and winter of 1921, and in some catchments in SE extend well into 1922 for SSI-12. In NEE flow deficits were extreme in cases, with severe deficits experienced throughout 1921. North-western areas again experienced extreme/severe deficits in winter 1923/1924 in Scotland, Northern Ireland, and SWESW for SSI-3.

Deleted: North East England

Deleted: 8

1933-1934

Severe and extreme drought began in winter 1933 in Scotland and Northern Ireland, with much of the country in extreme drought in 1934 (Figure 11 and Figure S9). The ES, northern England and northern parts of ANG appear to be less affected, although still show at least mild flow deficits. The most severe deficits across the country occur for the duration of 1934, and in some southerly catchments extend into the start of 1935. For SSI-3, deficits ended in the majority of catchments in spring 1934, but continued until the autumn in the south-east of England.

Deleted: S8

Deleted: east of Scotland

Deleted: Anglian region

1940s

The 1940s was a decade with multiple periods of drought across the country. The decade began with extreme/severe deficits in WS and parts of NEE. Drought conditions were generally mild in other regions with the exception of ANG and SE for SSI-12, where flows were mostly normal or above (Figure 11). During the remainder of the 1940s however, drought was more coherent across the UK in terms of occurrence (although not in terms of severity) for both accumulation periods. Other notable drought phases in the decade occurred in southern and central England and south Wales in 1944, which extend right into Scotland for SSI-3 (Figure S9); in WS and catchments across northern England, Northern Ireland and north Wales in 1946; across the UK in winter 1947 for SSI-3, and prolonged drought conditions (albeit mild) across much of England and Wales 1948-1950 with severe drought in NEE in 1949 for SSI-12.

Deleted: S8

Deleted: western Scotland

4 Discussion

While past studies have identified historic drought episodes in the UK (as summarised in the introduction), a detailed, quantitative assessment of hydrological droughts at the national scale has been lacking. This paper provides the first systematic characterisation and ranking of hydrological droughts for a period of ~125 years for the UK, using a network of near-natural catchments. In the following discussion, we compare the findings with previous studies, address the scientific and practical significance of the outcomes, before outlining key limitations and recommendations for future research.

Deleted: minimally disturbed

4.1 Historic hydrological droughts

Understanding historic drought occurrence, duration and severity is vital for drought risk estimation and management in any location, and provides a baseline against which future change can be assessed. For the UK, the primary national scale assessment of past droughts is MCW2007 and the companion report Cole and Marsh (2005). Here, we set our findings in the context of these previous assessments. Unsurprisingly, there is good agreement as to what constitute the most significant events at the national scale, for example: the ‘Long Drought’ period (1891-1910), 1933-1934, 1975-1976, 1995-1997. However, there are also some important differences. MCW2007 deliberately highlighted national scale events which had evidence of demonstrable societal impact, and so excluded some of the droughts identified here which were either more regionally focussed or lacked the supporting documentary evidence of impacts. Critical droughts for individual catchments may not be those that occurred nationally, so it is important to consider the most severe droughts on a catchment, or regional, basis. The focus here on characterisation of the identified events for catchments across the UK provides more detail than is provided by MWC2007 who quantified severity for only a handful of long-term hydrometeorological series in the north-west of England and East Anglia.

At the national scale, Jones and Lister (1998) used the drought deficit index to identify droughts in 15 catchments across England and Wales using reconstructed river flows from 1865 to 1993, assessing the severity of the 1989-1992 drought in the context of previous events. Over an 18 month accumulation period of the drought deficit index, the following events ranked as most severe 1975-1976, 1887-1888, 1905-1906, 1921-1922, 1933-1934 and 1943-1944. These events compare well with those identified here, with the exception of 1887-1888 which is outside of the reconstructed period. Inter-decadal variability is apparent in both sets of reconstructed droughts, with drought rich periods in the 1890s and 1940s. With just 15 catchments, Jones and Lister (1998) could not capture regional- and national-scale events. Here however, the national picture is more developed with space-time evolution of events, and systematic rankings shown for 108 UK catchments for the 125 year period 1891-2015, encompassing the most recent events, with analysis based on reconstructed flows modelled using robust methods (Smith et al., 2019).

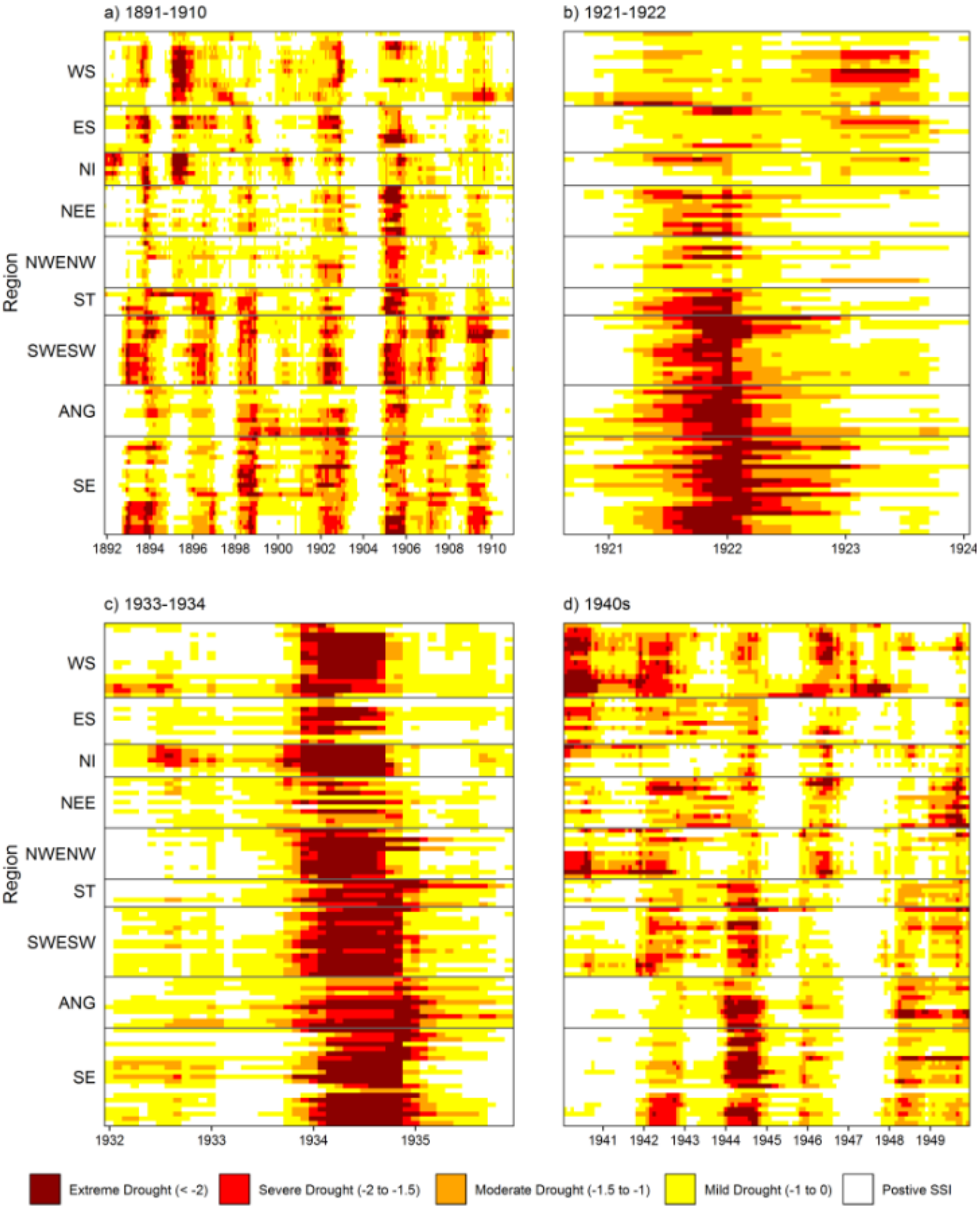
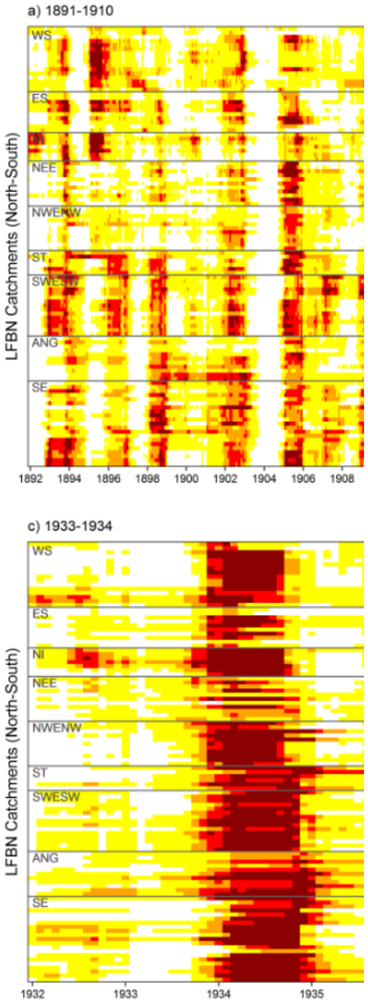


Figure 11 Heat maps of reconstructed SSI-12 for LFBN catchments, arranged roughly from north to south with one row per catchment and regions marked for clarity for a) the 'Long Drought' period (1890s-1910s), b) 1921-1922, c) 1933-1934 and d) the 1940s.

Deleted:



Deleted:

🟥 Extreme Drought (< -2) 🟥 Severe
🟨 Mild Drought (-1 to 0) ☐ Postive

Deleted: low flow benchmark

Our results also resonate with other historical drought studies in the UK (e.g. Fowler and Kilsby, 2002; Lennard et al., 2016; Spraggs et al., 2015; Rudd et al., 2017). These studies typically focussed on regional assessments using a small number of catchments or gauges. Although there were parallels with the results shown here (e.g. Spraggs et al. (2015) also find the 1989-1992 event to be the most severe for the river Lud (ANG) in river flow reconstructions from 1798-2010; and events identified in Yorkshire by Fowler and Kilsby (2002) corresponded to those in the top 10 rankings for NEE, such as SSI-12 for duration, accumulated deficit and mean deficit: 1905, 1940s, the mid 1960s and 1970s and early 1990s), their transferability is limited by their regional scope and differing methods of assessment.

Deleted: in ANG

Parallels with studies in Europe and at the continental scale are also evident, although few studies focus on hydrological droughts at the catchment scale, with most using meteorological drought indicators. Spinoni et al. (2015) used the Standardised Precipitation Index (SPI) to identify and rank events for Europe 1950-2010 and found that for Great Britain more severe events occurred in the earlier part of this time frame, with 1975-1976 ranking as the most severe for Great Britain, whilst 1959 was most extensive. Van der Schrier et al. (2006) extend further back in time (1901-2002), using meteorological drought indicators based on the Palmer Drought Severity Index. They found that the driest year occurred in 1947 followed by 1921 and 1950, with exceptionally dry summers in England in 1976 and 1921, and in Scotland in 1949, 1945 and 1946. Across the island of Ireland, Noone et al. (2017) found that the most severe events extracted from SPI derived from recovered rainfall data occurred in the mid-to-late 1800s, but also noted that all of the events within the top 10 rankings for the four event characteristics as used here, occurred before 1977. Although there were fewer top ranking events after the 1975-1976 event here, events of the 1990s and 2010-2012 did rank in the top 10 for both SSI-3 and SSI-12 (Figure S5 and Figure 7, respectively). The lower numbers of drought events post-1980 here and in Noone et al. (2017) are commensurate with increasing trends in runoff in northern and western parts of the UK (e.g. Hannaford, 2015). Although Hanel et al. (2018) did not include the British Isles in their analyses, they found that large-scale drought events occurred in 1921-22 and 1949-50 across Europe in terms of meteorological hydrological and agricultural drought. In terms of hydrological droughts, Sheffield et al. (2009) identified events at the continental scale from global VIC model outputs over 1950-2000: events in the 1960s and 1975-1976 ranked as the most severe across Europe (although were focussed in western and eastern Europe), with much of Europe also affected by drought in 1953-1954. In a low flows assessment using modelled reconstructions for over 650 catchments across France for the period 1800-2012, Caillouet et al. (2017) found that 1976 was the longest and most severe event in northern France. Given the spatial footprint of the event (Briffa et al., 2009) it is unsurprising that 1976 is similarly highly ranked in southern England in terms of accumulated and mean deficit (e.g. Figure 6 and Figure 7).

Deleted: S4

Formatted: Font: 11 pt

It is instructive to consider why the events identified in Figure 9 and Figure S7 were not considered major events by MCW2007 and others. The events of the late 1960s and early 1970s were somewhat

Deleted: S6

overshadowed by the 1975-1976 event in which there were dramatic impacts on water supplies and the environment across the UK (e.g. Doornkamp et al., 1980; Rodda and Marsh, 2011). Although the 1975-1976 event was a distinct event, the 20 year period between 1960 and 1979 can be seen to be drought rich in Figure 3 and Figure S2, within which events rank as most severe and fall within the top 10 (Figures 5 and 6, and Figures S3 and S6). In this study the 1940s ranked highly across the different event characteristics, and affected much of the country with flow deficits occurring somewhere in all months throughout this period (Figure 11 & Figure S2). Although 1943-1944 was classed as a major hydrological event by MCW2007 the documentary evidence to support the physical manifestation of the drought was lacking in the post-War period. As such, the importance of the hydrological droughts of the 1940s are probably understated, as was found by Rudd et al. (2017), and the findings of this study (along with regional assessments such as Spraggs et al. (2015) who found it to be a significant event in East Anglia), indicate it was a national scale event (Figure 11d) which may have had substantial impacts on society and the environment.

Deleted: (e.g. Doornkamp et al., 1980; Rodda and Marsh, 2011)

Deleted: S1

Deleted: S1

Deleted: is

It is of course important to re-emphasise the hydrological focus of this study. Although the 1959 and 2004 events were identified here, they were not often ranked as most severe (with the exception of 1959 for SSI-12 maximum intensity, Figure 10). These events may be better characterised by rainfall (1959) or groundwater (2004-2006) drought indicators. The addition of impact information (as in MWC2007 or Noone et al. (2017), for example) would shed more light on these events, the severity of deficits and their impacts (see Section 4.3).

The benefit of using of the two accumulation periods is highlighted when considering the 1984 event, which was not identified using SSI-12, but was ranked as most severe for 16 catchments across western Britain when using SSI-3. Figure 5 and Figure S3 also show the benefit of utilising the different event characteristics as different events are ranked as most severe when each of the characteristics is considered. This is particularly important for water managers who may be dependent on water sources with differing levels of responsiveness for their supply; such as single season reservoirs, or those with more memory that respond more slowly, such as groundwater dominated river flows.

Deleted: S5

4.2 Applications

The extracted events and new analyses presented here can support further work on the trends and variability of hydrological droughts in the UK. Although work has been undertaken to understand the link between droughts in the UK and large-scale atmospheric forcings (e.g. Folland et al., 2015; Svensson and Hannaford, 2019), this longer, wider set of drought event reconstructions provides a much broader dataset to assess large-scale patterns which cause the clustering of drought events. A better understanding of the relationship between large-scale atmospheric forcings and drought event characteristics would be useful in the context of drought monitoring, early warning and forecasting applications.

Deleted: (e.g. Folland et al., 2015)

Using reconstructed river flow data (opposed to using observed data) not only extend record lengths on average by ~75 years, but when considering the identified and characterised events provides a much larger pool of events to work with. Across all catchments, ~67% and ~65% of events extracted from the SSI-12 and SSI-3, respectively) occurred before the observed records began. This highlights the benefit of the long-term view and increasing the pool of events to improve our understanding of past hydrological drought behaviours. Our findings have important implications for those considering hydrological drought risk, particularly for water resources planners. These reconstructed drought series can be applied in the stress testing of water resource systems for water resources management and drought plans. Most directly, the results can assist in conventional stress tests using the worst droughts on record (e.g. Environment Agency, 2015), but can also inform 'scenario' based stress tests based on synthetic design droughts (e.g. Watts et al., 2012; Anderton et al., 2015). Similarly, the results can provide inputs to – or corroboration for – the stochastic drought generation techniques that are increasingly used in UK water resource and drought planning (e.g. Atkins, 2016).

Some studies (e.g. Spraggs et al., 2015; Lennard et al., 2016) have demonstrated that extending the hydrological records does not improve water resources planning in particular water supply regions of the UK. However, their regional focus and infrastructure modelling limits their applicability to other locations where earlier droughts may have substantial impacts on supplies. The results presented here demonstrate that in many regions of the UK, some of the most severe hydrological droughts occurred in the late 19th and early 20th centuries. Further work is required to run such sequences through water supply system models to understand the impacts on drought risk assessments and thus on management plans. But the data and knowledge developed here provides a consistent, national resource for such studies, which is particularly important as more joined up regional- and national planning is becoming a key priority in the UK (Water UK, 2016; National Infrastructure Commission, 2018). The regional differences in the most severe events over the past ~125 years and the range of event characteristics (i.e. accumulated deficit, duration, mean deficit and maximum intensity) shown here provide a valuable toolkit for assessing hydrological droughts across the country. To this end, results for individual catchments (the full set of 303 catchments for which reconstructions are available) and additional accumulation periods can be explored using the 'UK Hydrological Drought Explorer' (https://shiny-apps.ceh.ac.uk/hydro_drought_explorer/), including SSI timeseries, extracted events and the most severe droughts (ranked by the four event characteristics) – see the Data Availability section.

Deleted: approaches

Deleted: also

Deleted:

4.3 Data limitations & future work

The SSI was derived from daily river flow reconstructions (Smith et al., 2018), extending the gauged record of the LFBN catchments by, on average, more than 75 years, and at most 86 years. When deriving the SSI, uncertainties may arise from fitting the selected distribution (e.g. Stagge et al., 2015; Svensson et al., 2017); however, the Tweedie distribution has been found to fit well for UK river flow data and is recommended by Svensson et al. (2017). Smith et al. (2019) assessed the performance of the modelled flow reconstructions and the derived SSI for 303 UK catchments (including the LFBN). Although the SSI was found to exacerbate any model errors in the flow simulations and the exact magnitude of flow deficits may not be well captured by the reconstructed SSI, the peaks and troughs and the drought events extracted from the reconstructions compared well to those from observed flows (using the same identification methodology as used here; Smith et al., 2019). The relative rankings of the extracted drought events presented here should, therefore, be well captured.

The flow reconstructions of Smith et al. (2018) provide the top 500 ensemble members for each of the LFBN catchments (within the full set of 303 catchments). However, in this study, the single best performing model run (LHS1) was used for each catchment without accounting for model uncertainty due to the computational implications of deriving the SSI using the Tweedie distribution for 500 model parameterisations for each catchment. Due to the identified uncertainties in deficit magnitudes in some catchments by Smith et al. (2019), utilising the ensemble data in future studies will provide more confidence in the extraction of drought events that are near the threshold of “severe” drought (i.e. an SSI value of -1.5).

Deleted: , h

Here, the SSI was calculated using a reference period of 1961-2010 for consistency with companion datasets of gridded Standardised Precipitation Index for the UK (Tanguy et al., 2015; Tanguy et al., 2017). Although this period encompasses well defined flood/drought rich and flood/drought poor periods, the derived SSI and extracted and ranked drought events are derived relative to this period. As high/low rainfall and river flows become more extreme in the future (e.g. Prudhomme et al., 2014), these data should be used with caution for future assessments.

Although reconstruction modelling approaches are valuable, providing otherwise unavailable data for historic events, the limitations of the approach should be recognised. They provide systematic series for the past, but modelling approaches do not address non-stationarities in catchment response or land use change etc. As such, there remains a need for long-term hydrometric data rescue and recovery (e.g. at Wendover Springs, Bayliss et al., 2004), curation (e.g. Dixon et al., 2013), and the incorporation of additional strands of evidence (e.g. documentary, epigraphic and paleohydrological) to supplement and bolster the analysis of hydrological extremes (e.g. Kjeldsen et al., 2014).

The long time series of the SSI and the extracted drought events presented here provide the potential for national scale assessments of trends, changes in timing and seasonality of drought events across the UK. However, when managing and planning for drought, it is also important to consider meteorological and groundwater droughts. Recovered and reconstructed data from the Historic Droughts project (e.g. Bloomfield et al., 2018; Durant and Counsell, 2018) will enable a more holistic analysis of UK drought at both the national and regional scale. By design drought impacts were not considered here; however,

Deleted: However, it is not only hydrological (streamflow) droughts which are important to understand when managing and planning for drought, meteorological and groundwater droughts also play an important role. Groundwater is critical for UK water supply (particularly in south-east England), and as such it will be necessary to integrate streamflow and groundwater drought reconstruction components to fully assess the impact of the droughts on water supply systems.

Deleted: this

Deleted:

this paper presents a systematic characterisation of UK droughts which can be analysed in conjunction with impact information from a range of sources in the future, for example the European Drought Impact report Inventory (Stahl et al., 2016) and references to drought from British newspapers (e.g. Baker et al., 2019).

5 Conclusions

This study presents timelines of historic reconstructed droughts for 108 near-natural catchments extracted from the Standardised Streamflow Index (SSI) for three and twelve month accumulation periods. It characterises and ranks these past drought events and assesses how relative rankings for each characteristic vary geographically for the first time in the UK. It also provides a fuller understanding of the evolution and characteristics of major, nationally important droughts from the pre-observation period. The results here reflect the work of previous studies in the UK and at the European scale, identifying well known events as extreme events for the UK (e.g. 1976), but also sheds light on events of the 20th century that have not previously been considered as significant (whether due to a lack of data or evidence of impact), such as the droughts of the 1940s and early 1970s. Results highlight that a range of timescales, or accumulation periods, should be considered when assessing drought severity and hazard in different locations and for different sectors dependent on water sources with varying response time. By using continuous time series of reconstructed river flow, consistent, objective drought event identification methods and quantitative appraisal of multiple drought characteristics, this study provides a more longitudinal view of drought occurrence and characteristics over a ~125 year period for the UK, with the higher resolution, catchment scale detail important for both science and drought planning applications of the future.

Deleted: ¶
Whilst this paper uses objective, systematic methods to identify, characterise and rank UK hydrological droughts, there was (by design) no consideration of the impacts of each drought. The complex propagation and development processes of drought events and the effect of management actions may mean that although a drought may be highly ranked in terms of its physical characteristics (duration, accumulated deficit, mean deficit etc.), there may not have been equivalent impacts on the environment or society (e.g. as was found by (e.g. as was found by Lennard et al., 2016) for the Severn Trent region water supplies). However, this paper provides an independent characterisation of UK droughts which can in future be analysed in conjunction with impact information from a range of sources, for example: the European Drought Impact report Inventory (Stahl et al., 2016); references to drought from legislation (e.g. Lange and Golomoz, 2018), agricultural media (e.g. Rey et al., 2018) or British newspapers (e.g. Baker et al., 2019).¶

Data Availability

Reconstructed daily streamflow: freely available for download via the Environmental Data Information Centre along with associated metadata on the models performance (Smith et al., 2018). The performance of the model in each catchment, as well as the reconstructed daily river flow timeseries, can be explored using an interactive web application, the 'UK Reconstructed Flow Data Explorer', at https://shiny-apps.ceh.ac.uk/reconstruction_explorer/.

Standardised Streamflow Index: freely available for download via the Environmental Data Information Centre (Barker et al., 2018b). These SSI data, along with further event analyses can be explored for the LFBN using an interactive web application, the 'UK Hydrological Drought Explorer', at https://shiny-apps.ceh.ac.uk/hydro_drought_explorer/.

Author Contributions

Lucy Barker, Jamie Hannaford and Simon Parry discussed and developed the aims of the paper. Lucy Barker was responsible for the data analysis and visualisation. Lucy Barker and Jamie Hannaford prepared the original manuscript, with contributions from Simon Parry, Katie Smith, Maliko Tanguy and Christel Prudhomme.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

This research is an outcome of the UK Drought & Water Scarcity Programme Historic Droughts project, financial support was provided by the UK Natural Environment Research Council [NE/L01061X/1].

References

Adaptation Sub-Committee: UK Climate Change Risk Assessment 2017: Synthesis Report: priorities for the next five years, Adaptation Sub-Committee of the Committee on Climate Change, London, 2016.

Anderton, S., Ledbetter, R., and Prudhomme, C.: Understanding the performance of water supply systems during mild to extreme droughts, Environment Agency, Bristol, 2015.

Atkins: Thames Water Stochastic Resource Modelling: Stage 2&3 Report, 2016.

Bachmair, S., Stahl, K., Collins, K., Hannaford, J., Acreman, M., Svoboda, M., Knutson, C., Smith, K. H., Wall, N., Fuchs, B., Crossman, N. D., and Overton, I. C.: Drought indicators revisited: the need for a wider consideration of environment and society, Wiley Interdisciplinary Reviews: Water, 3, 516-536, doi:10.1002/wat2.1154, 2016a.

Bachmair, S., Svensson, C., Hannaford, J., Barker, L., and Stahl, K.: A quantitative analysis to objectively appraise drought indicators and model drought impacts, Hydrology and Earth System Sciences, 20, 2589-2609, 2016b.

Baker, H., Fry, M., and Bachiller-Jareno, N.: Historic droughts inventory of references from British twentieth-century newspapers 1900-1999, UK Data Service, 10.5255/UKDA-SN-853196, 2019.

Barker, L., Mastrantonas, N., Lewis, M., and Clemas, S.: Hydrological summary for the United Kingdom: July 2018, Wallingford, UK, 2018a.

Barker, L. J., Hannaford, J., Chiverton, A., and Svensson, C.: From meteorological to hydrological drought using standardised indicators, Hydrology and Earth System Sciences, 20, 2483-2505, 2016.

Barker, L. J., Smith, K. A., Svensson, C., Tanguy, M., and Hannaford, J.: Historic Standardised Streamflow Index (SSI) using Tweedie distribution with standard period 1961-2010 for 303 UK catchments (1891-2015), NERC Environmental Information Data Centre, 10.5285/58ef13a9-539f-46e5-88ad-c89274191ff9, 2018b.

Bayliss, A., Norris, J., and Marsh, T.: The Wendover Springs record: An insight into the past and a benchmark for the future, Weather, 59, 267-271, 2004.

Bloomfield, J. P., Marchant, B. P., and Wang, L.: Historic Standardised Groundwater level Index (SGI) for 54 UK boreholes (1891-2015), NERC Environmental Information Data Centre, 10.5285/d92c91ec-2f96-4ab2-8549-37d520dbd5fc, 2018.

Briffa, K., Van Der Schrier, G., and Jones, P.: Wet and dry summers in Europe since 1750: evidence of increasing drought, International Journal of Climatology: A Journal of the Royal Meteorological Society, 29, 1894-1905, 2009.

Brown, C. M., Lund, J. R., Cai, X., Reed, P. M., Zagona, E. A., Ostfeld, A., Hall, J., Characklis, G. W., Yu, W., and Brekke, L.: The future of water resources systems analysis: Toward a scientific framework for sustainable water management, Water Resources Research, 51, 6110-6124, 2015.

Caillouet, L., Vidal, J. P., Sauquet, E., Devers, A., and Graff, B.: Ensemble reconstruction of spatio-temporal extreme low-flow events in France since 1871, Hydrol. Earth Syst. Sci., 21, 2923-2951, 10.5194/hess-21-2923-2017, 2017.

Cole, G., and Marsh, T.: Major Droughts in England and Wales from 1800-and Evidence of Impact, Environment Agency, Bristol, 2005.

Coron, L., Thirel, G., Delaigue, O., Perrin, C., and Andréassian, V.: The suite of lumped GR hydrological models in an R package, Environmental Modelling & Software, 94, 166-171, 2017.

Dixon, H., Hannaford, J., and Fry, M. J.: The effective management of national hydrometric data: experiences from the United Kingdom, Hydrological Sciences Journal, 58, 1383-1399, 2013.

Doornkamp, J., Gregory, K., and Burn, A.: Atlas of Drought 1975-1976, Institute of British Geographers, London, 1980.

Environment Agency: Water for People and the Environment: Water resources strategy for England and Wales, Environment Agency, Bristol, UK, 2009.

Environment Agency, and Natural Resources Wales: Water stressed areas - final classification, Environment Agency & Natural Resources Wales, Bristol/Cardiff, 2013.

Write a drought plan: How to write a water company drought plan: https://www.gov.uk/guidance/write-a-drought-plan, 2015.

Folland, C. K., Hannaford, J., Bloomfield, J. P., Kendon, M., Svensson, C., Marchant, B. P., Prior, J., and Wallace, E.: Multi-annual droughts in the English Lowlands: a review of their characteristics and climate drivers in the winter half-year, Hydrol. Earth Syst. Sci., 19, 2353-2375, 10.5194/hess-19-2353-2015, 2015.

Fowler, H., and Kilsby, C.: A weather-type approach to analysing water resource drought in the Yorkshire region from 1881 to 1998, Journal of Hydrology, 262, 177-192, 2002.

Hanel, M., Rakovec, O., Markonis, Y., Máca, P., Samaniego, L., Kyselý, J., and Kumar, R.: Revisiting the recent European droughts from a long-term perspective, Scientific Reports, 8, 9499, 10.1038/s41598-018-27464-4, 2018.

Hannaford, J.: Climate-driven changes in UK river flows:A review of the evidence, Progress in Physical Geography: Earth and Environment, 39, 29-48, 10.1177/0309133314536755, 2015.

Harrigan, S., Hannaford, J., Muchan, K., and Marsh, T.: Designation and trend analysis of the updated UK Benchmark Network of river flow stations: The UKBN2 dataset, Hydrology Research, 10.2166/nh.2017.058, 2017.

Harrigan, S., Prudhomme, C., Parry, S., Smith, K., and Tanguy, M.: Benchmarking ensemble streamflow prediction skill in the UK, Hydrology and Earth System Sciences, 22, 2023-2039, 2018.

Hollis, D., McCarthy, M., Kendon, M., Legg, T., and Simpson, I.: HadUK-Grid—A new UK dataset of gridded climate observations, Geoscience Data Journal, 0, 10.1002/gdj3.78, 2019.

Jones, P.: Riverflow reconstruction from precipitation data, Journal of Climatology, 4, 171-186, 1984.

Jones, P., and Lister, D.: Riverflow reconstructions for 15 catchments over England and Wales and an assessment of hydrologic drought since 1865, International Journal of Climatology: A Journal of the Royal Meteorological Society, 18, 999-1013, 1998.

Jones, P. D., Lister, D. H., Wilby, R. L., and Kostopoulou, E.: Extended riverflow reconstructions for England and Wales, 1865–2002, International Journal of Climatology, 26, 219-231, 10.1002/joc.1252, 2006.

Kendon, M., Marsh, T., and Parry, S.: The 2010–2012 drought in England and Wales, Weather, 68, 88-95, doi:10.1002/wea.2101, 2013.

Kjeldsen, T., Macdonald, N., Lang, M., Mediero, L., Albuquerque, T., Bogdanowicz, E., Brazdil, R., Castellarin, A., David, V., and Fleig, A.: Documentary evidence of past floods in Europe and their utility in flood frequency estimation, Journal of Hydrology, 517, 963-973, 2014.

Kjeldsen, T. R., and Prosdocimi, I.: Assessing the element of surprise of record-breaking flood events, Journal of Flood Risk Management, 11, S541-S553, 10.1111/jfr3.12260, 2018.

Lennard, A. T., Macdonald, N., Clark, S., and Hooke, J. M.: The application of a drought reconstruction in water resource management, Hydrology Research, 47, 646-659, 10.2166/nh.2015.090, 2016.

Marsh, T.: The 2004–2006 drought in southern Britain, Weather, 62, 191-196, 2007.

Marsh, T., Cole, G., and Wilby, R.: Major droughts in England and Wales, 1800–2006, Weather, 62, 87-93, 10.1002/wea.67, 2007.

Met Office: HadUK-Grid gridded and regional average climate observations for the UK, Centre for Environmental Data Analysis, 10.5285/4dc8450d889a491ebb20e724debe2dfb, 2018.

Met Office: MIDAS Open: UK daily rainfall data, v201901, Centre for Environmental Data Analysis, 10.5285/ec54d5e5288a4ebb8c7ad2a1ef6aec42, 2019.

National Infrastructure Commission: Preparing for a drier future: England's water infrastructure needs, 2018.

Noone, S., Broderick, C., Duffy, C., Matthews, T., Wilby, R. L., and Murphy, C.: A 250-year drought catalogue for the island of Ireland (1765–2015), International Journal of Climatology, 37, 239-254, 10.1002/joc.4999, 2017.

Parry, S., Wilby, R. L., Prudhomme, C., and Wood, P. J.: A systematic assessment of drought termination in the United Kingdom, Hydrol. Earth Syst. Sci., 20, 4265-4281, 10.5194/hess-20-4265-2016, 2016.

Perrin, C., Michel, C., and Andréassian, V.: Improvement of a parsimonious model for streamflow simulation, Journal of Hydrology, 279, 275-289, https://doi.org/10.1016/S0022-1694(03)00225-7, 2003.

Pfister, C., Weingartner, R., and Luterbacher, J.: Hydrological winter droughts over the last 450 years in the Upper Rhine basin: a methodological approach, Hydrological Sciences Journal, 51, 966-985, 10.1623/hysj.51.5.966, 2006.

Prudhomme, C., Parry, S., Hannaford, J., Clark, D. B., Hagemann, S., and Voss, F.: How Well Do Large-Scale Models Reproduce Regional Hydrological Extremes in Europe?, Journal of Hydrometeorology, 12, 1181-1204, 10.1175/2011jhm1387.1, 2011.

Prudhomme, C., Giuntoli, I., Robinson, E. L., Clark, D. B., Arnell, N. W., Dankers, R., Fekete, B. M., Franssen, W., Gerten, D., Gosling, S. N., Hagemann, S., Hannah, D. M., Kim, H., Masaki, Y., Satoh, Y., Stacke, T., Wada, Y., and Wisser, D.: Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment, Proceedings of the National Academy of Sciences, 111, 3262-3267, 10.1073/pnas.1222473110, 2014.

Rodda, J., and Marsh, T.: The 1975-76 Drought-a contemporary and retrospective review, National Hydrological Monitoring Programme series, 2011.

Rudd, A. C., Bell, V. A., and Kay, A. L.: National-scale analysis of simulated hydrological droughts (1891–2015), Journal of Hydrology, 550, 368-385, https://doi.org/10.1016/j.jhydrol.2017.05.018, 2017.

Sheffield, J., Andreadis, K. M., Wood, E. F., and Lettenmaier, D. P.: Global and Continental Drought in the Second Half of the Twentieth Century: Severity–Area–Duration Analysis and Temporal Variability of Large-Scale Events, Journal of Climate, 22, 1962-1981, 10.1175/2008jcli2722.1, 2009.

Smith, K. A., Tanguy, M., Hannaford, J., and Prudhomme, C.: Historic reconstructions of daily river flow for 303 UK catchments (1891-2015), NERC Environmental Information Data Centre, 10.5285/f710bed1-e564-47bf-b82c-4c2a2fe2810e, 2018.

Smith, K. A., Barker, L. J., Tanguy, M., Parry, S., Harrigan, S., Legg, T., Prudhomme, C., and Hannaford, J.: A Multi-Objective Ensemble Approach to Hydrological Modelling in the UK: An Application to Historic Drought Reconstruction, Hydrology and Earth System Sciences, 23, 3247-3268, https://doi.org/10.5194/hess-23-3247-2019, 2019.

Spinoni, J., Naumann, G., Vogt, J. V., and Barbosa, P.: The biggest drought events in Europe from 1950 to 2012, Journal of Hydrology: Regional Studies, 3, 509-524, 2015.

Spraggs, G., Peaver, L., Jones, P., and Ede, P.: Re-construction of historic drought in the Anglian Region (UK) over the period 1798–2010 and the implications for water resources and drought management, Journal of Hydrology, 526, 231-252, https://doi.org/10.1016/j.jhydrol.2015.01.015, 2015.

Stagge, J. H., Tallaksen, L. M., Gudmundsson, L., Van Loon, A. F., and Stahl, K.: Candidate Distributions for Climatological Drought Indices (SPI and SPEI), International Journal of Climatology, 35, 4027-4040, 10.1002/joc.4267, 2015.

Stahl, K., Kohn, I., Blauhut, V., Urquijo, J., De Stefano, L., Acácio, V., Dias, S., Stagge, J. H., Tallaksen, L. M., Kampragou, E., Van Loon, A. F., Barker, L. J., Melsen, L. A., Bifulco, C., Musolino, D., de Carli, A., Massarutto, A., Assimacopoulos, D., and Van Lanen, H. A. J.: Impacts of European drought events: insights from an international database of text-based reports, Nat. Hazards Earth Syst. Sci., 16, 801-819, 10.5194/nhess-16-801-2016, 2016.

Svensson, C., Hannaford, J., and Prosdocimi, I.: Statistical distributions for monthly aggregations of precipitation and streamflow in drought indicator applications, Water Resources Research, 53, 999-1018, 2017.

Svensson, C., and Hannaford, J.: Oceanic conditions associated with Euro-Atlantic high pressure and UK drought, Environmental Research Communications, 1, 101001, 10.1088/2515-7620/ab42f7, 2019.

Tanguy, M., Hannaford, J., Barker, L., Svensson, C., Kral, F., and Fry, M.: Gridded Standardized Precipitation Index (SPI) using gamma distribution with standard period 1961-2010 for Great Britain [SPIgamma61-10], NERC Environmental Information Data Centre, 10.5285/94c9eaa3-a178-4de4-8905-dbfab03b69a0, 2015.

Tanguy, M., Fry, M., Svensson, C., and Hannaford, J.: Historic Gridded Standardised Precipitation Index for the United Kingdom 1862-2015 (generated using gamma distribution with standard period 1961-2010) v4, NERC Environmental Information Data Centre, 10.5285/233090b2-1d14-4eb9-9f9c-3923ea2350ff, 2017.

Tanguy, M., Prudhomme, C., Smith, K., and Hannaford, J.: Historical gridded reconstruction of potential evapotranspiration for the UK, Earth System Science Data, 10, 951-968, 2018.

Thompson, V., Dunstone, N. J., Scaife, A. A., Smith, D. M., Slingo, J. M., Brown, S., and Belcher, S. E.: High risk of unprecedented UK rainfall in the current climate, Nature Communications, 8, 107, 10.1038/s41467-017-00275-3, 2017.

Todd, B., Macdonald, N., Chiverrell, R. C., Caminade, C., and Hooke, J. M.: Severity, duration and frequency of drought in SE England from 1697 to 2011, Climatic Change, 121, 673-687, 10.1007/s10584-013-0970-6, 2013.

Van der Schrier, G., Briffa, K., Jones, P., and Osborn, T.: Summer moisture variability across Europe, Journal of Climate, 19, 2818-2834, 2006.

Van Lanen, H., Wanders, N., Tallaksen, L., and Van Loon, A.: Hydrological drought across the world: impact of climate and physical catchment structure, Hydrology and Earth System Sciences, 17, 1715-1732, 2013.

Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A. J., Tallaksen, L. M., Uijlenhoet, R., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangecroft, S., Wanders, N., and Van Lanen, H. A. J.: Drought in the Anthropocene, Nature Geoscience, 9, 89, 10.1038/ngeo2646, 2016.

Vicente-Serrano, S. M., López-Moreno, J. I., Beguería, S., Lorenzo-Lacruz, J., Azorin-Molina, C., and Morán-Tejeda, E.: Accurate computation of a streamflow drought index, Journal of Hydrologic Engineering, 17, 318-332, 2011.

Water UK: Water resources long term planning framework (2015-2065), Water UK, London, 2016.

Watts, G., von Christierson, B., Hannaford, J., and Lonsdale, K.: Testing the resilience of water supply systems to long droughts, Journal of Hydrology, 414, 255-267, 2012.

Watts, G., Battarbee, R. W., Bloomfield, J. P., Crossman, J., Daccache, A., Durance, I., Elliott, J. A., Garner, G., Hannaford, J., Hannah, D. M., Hess, T., Jackson, C. R., Kay, A. L., Kernan, M., Knox, J., Mackay, J., Monteith, D. T., Ormerod, S. J., Rance, J., Stuart, M. E., Wade, A. J., Wade, S. D., Weatherhead, K., Whitehead, P. G., and Wilby, R. L.: Climate change and water in the UK – past changes and future prospects, Progress in Physical Geography, 39, 6-28, 10.1177/0309133314542957, 2015.

Wilhite, D. A., Hayes, M. J., Knutson, C., and Smith, K. H.: Planning for Drought: Moving From Crisis to Risk Management 1, JAWRA Journal of the American Water Resources Association, 36, 697-710, 2000.

Supplementary information

Table S1 The 108 LFBN catchments used in this study, their hydroclimate region and area (from: National River Flow Archive, 2019). For more information about catchments see the National River Flow Archive (www.nrfa.ceh.ac.uk/). The nine case study catchments are marked with an asterisk.

NRFA Station Number	Catchment Name	Hydroclimate Region	Area (km^2)
3003	Oykel at Easter Turnaig	WS	330.7
7001	Findhorn at Shenachie	WS	415.6
8004	Avon at Delnashaugh	ES	542.8
8009	Dulnain at Balnaan Bridge	ES	272.2
12001	Dee at Woodend	ES	1370
12005	Muick at Invermuick	ES	110
16003	Ruchill Water at Cultybraggan	ES	99.5
17005	Avon at Polmonthill	ES	195.3
*18001	Allan Water at Kinbuck	ES	161
20007	Gifford Water at Lennoxlove	ES	64
21017	Ettrick Water at Brockhoperig	ES	37.5
21024	Jed Water at Jedburgh	ES	139
22001	Coquet at Morwick	NEE	569.8
23004	South Tyne at Haydon Bridge	NEE	751.1
24004	Bedburn Beck at Bedburn	NEE	74.9
25006	Greta at Rutherford Bridge	NEE	86.1
26003	Foston Beck at Foston Mill	NEE	57.2
*27035	Aire at Kildwick Bridge	NEE	282.3
27042	Dove at Kirkby Mills	NEE	59.2
27047	Snaizeholme Beck at Low Houses	NEE	10.2
27051	Crimple at Burn Bridge	NEE	8.1
27071	Swale at Crakehill	NEE	1363
27073	Brompton Beck at Snainton Ings	NEE	12.9
28046	Dove at Izaak Walton	ST	83
28072	Greet at Southwell	ST	46.2
*29003	Lud at Louth	ANG	55.2
29009	Ancholme at Toft Newton	ANG	27.2
30004	Lymn at Partney Mill	ANG	61.6
30012	Stainfield Beck at Cream Poke Farm	ANG	37.4
30015	Cringle Brook at Stoke Rochford	ANG	50.5
32003	Harpers Brook at Old Mill Bridge	ANG	74.3
33018	Tove at Cappenham Bridge	ANG	138.1
33029	Stringside at Whitebridge	ANG	98.8
34011	Wensum at Fakenham	ANG	161.9
36003	Box at Polstead	ANG	53.9
37005	Colne at Lexden	ANG	238.2
38026	Pincey Brook at Sheering Hall	SE	54.6
*39019	Lambourn at Shaw	SE	234.1
39020	Coln at Bibury	SE	106.7
39025	Enborne at Brimpton	SE	147.6
39028	Dun at Hungerford	SE	101.3
39034	Evenlode at Cassington Mill	SE	430
40011	Great Stour at Horton	SE	345

NRFA Station Number	Catchment Name	Hydroclimate Region	Area (km^2)
41022	Lod at Halfway Bridge	SE	52
41025	Loxwood Stream at Drungewick	SE	91.6
41027	Rother at Princes Marsh	SE	37.2
41029	Bull at Lealands	SE	40.8
42003	Lymington at Brockenhurst	SE	98.9
42008	Cheriton Stream at Sewards Bridge	SE	75.1
43014	East Avon at Upavon	SE	85.78
44006	Sydling Water at Sydling St Nicholas	SE	12.4
45005	Otter at Dotton	SWESW	202.5
46005	East Dart at Bellever	SWESW	21.5
47009	Tiddy at Tideford	SWESW	37.2
48003	Fal at Tregony	SWESW	87
49004	Gannel at Gwills	SWESW	41
50002	Torridge at Torrington	SWESW	663
52010	Brue at Lovington	SE	135.2
52016	Currypool Stream at Currypool Farm	SE	15.7
53006	Frome (Bristol) at Frenchay	SE	148.9
53008	Avon at Great Somerford	SE	303
53009	Wellow Brook at Wellow	SE	72.6
53017	Boyd at Bitton	SE	47.9
*54008	Teme at Tenbury	ST	1134.4
54018	Rea Brook at Hookagate	ST	178
54025	Dulas at Rhos-y-pentref	ST	52.7
54034	Dowles Brook at Oak Cottage	ST	40.8
55014	Lugg at Byton	SWESW	203.3
55016	Ithon at Disserth	SWESW	358
55026	Wye at Ddol Farm	SWESW	174
55029	Monnow at Grosmont	SWESW	354
56013	Yscir at Pont-Ar-Yscir	SWESW	62.8
*57004	Cynon at Abercynon	SWESW	106
60002	Cothi at Felin Mynachdy	SWESW	297.8
60003	Taf at Clog-y-Fran	SWESW	217.3
62001	Teifi at Glanteifi	SWESW	893.6
65001	Glaslyn at Beddgelert	NWENW	68.6
65005	Erch at Pencaenewydd	NWENW	18.1
66004	Wheeler at Bodfari	NWENW	62.9
67018	Dee at New Inn	NWENW	53.9
68005	Weaver at Audlem	NWENW	207
72005	Lune at Killington	NWENW	219
72014	Conder at Galgate	NWENW	28.5
73005	Kent at Sedgwick	NWENW	209
73011	Mint at Mint Bridge	NWENW	65.8
*75017	Ellen at Bullgill	NWENW	96
76014	Eden at Kirkby Stephen	NWENW	69.4
77004	Kirtle Water at Mossknowe	WS	72
78004	Kinnel Water at Redhall	WS	76.1
79002	Nith at Friars Carse	WS	799
79004	Scar Water at Capenoch	WS	142

NRFA Station Number	Catchment Name	Hydroclimate Region	Area (km^2)
*81002	Cree at Newton Stewart	WS	368
81004	Bladnoch at Low Malzie	WS	334
83006	Ayr at Mainholm	WS	574
83010	Irvine at Newmilns	WS	72.8
84022	Duneaton at Maidencots	WS	110.3
85003	Falloch at Glen Falloch	WS	80.3
90003	Nevis at Claggan	WS	69.2
93001	Carron at New Kelso	WS	137.8
94001	Ewe at Poolewe	WS	441.1
96002	Naver at Apigill	WS	477
201008	Derg at Castlederg	NI	335.4
202002	Faughan at Drumahoe	NI	273.1
203028	Agivey at Whitehill	NI	100.5
*203042	Crumlin at Cidercourt Bridge	NI	55.3
204001	Bush at Seneirl Bridge	NI	299.2
205008	Lagan at Drumiller	NI	84.6
206001	Clanrye at Mountmill Bridge	NI	120.3

Table S2 Catchments and months with missing SSI-3 values

Catchment	Months with missing SSI-3 values	Impact
29003 Lud at Louth	2007-09	No impact on the extracted drought events
40011 Great Stour at Horton	1921-12	Splits a drought event which without the missing value would be the longest (and most severe in terms of accumulated deficit) event in this catchment
54034 Dowles Brook at Oak Cottage	2007-07; 2007-08	No impact on the extracted drought events
72014 Conder at Galgate	1907-07	No impact on the extracted drought events

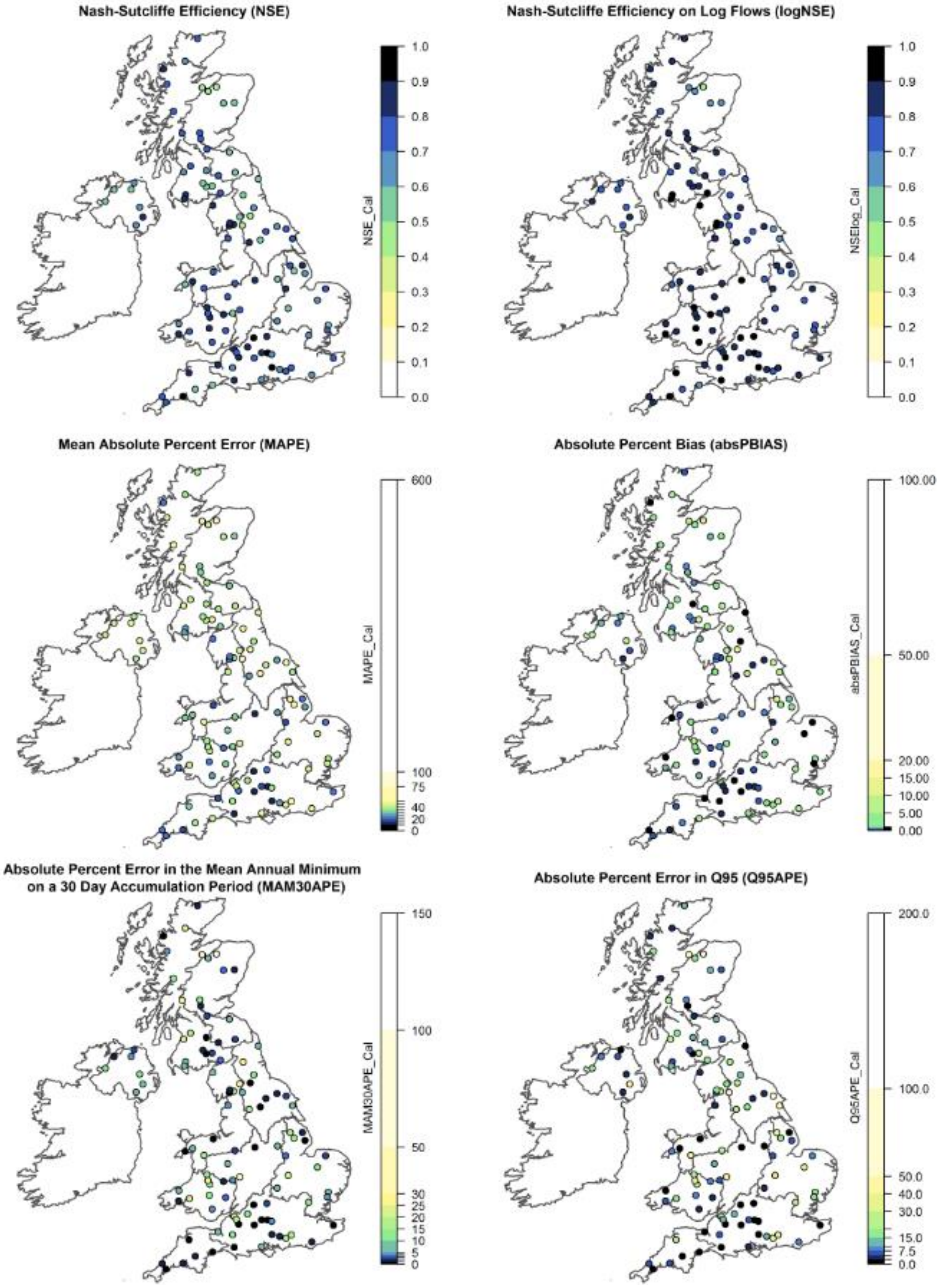


Figure S1 Model performance metrics from Smith et al. (2018) for the 108 LFBN catchments used in this study. Darker colours indicate better model performance.

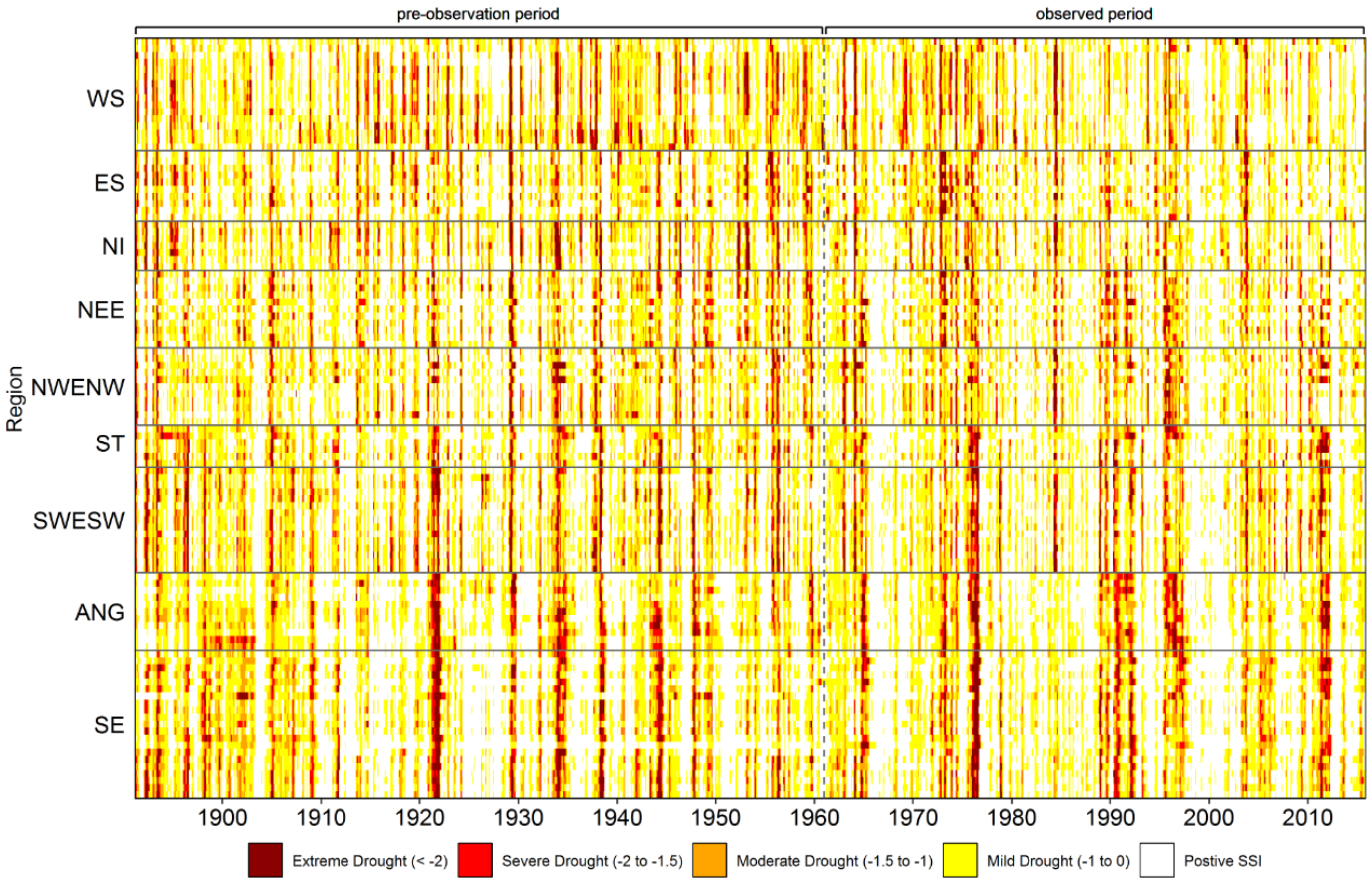


Figure S2 Heatmap of SSI-3 for LFBN catchments (arranged roughly from north to south on the y-axis with one row per catchment and regions marked for clarity) from 1891 to 2015.

Figure S3 Extracted events from SSI-3 and their characteristics for the nine case study catchments, plotted at the midpoint of the event. The size of each point is proportional to the maximum intensity and the colour indicates the mean deficit.

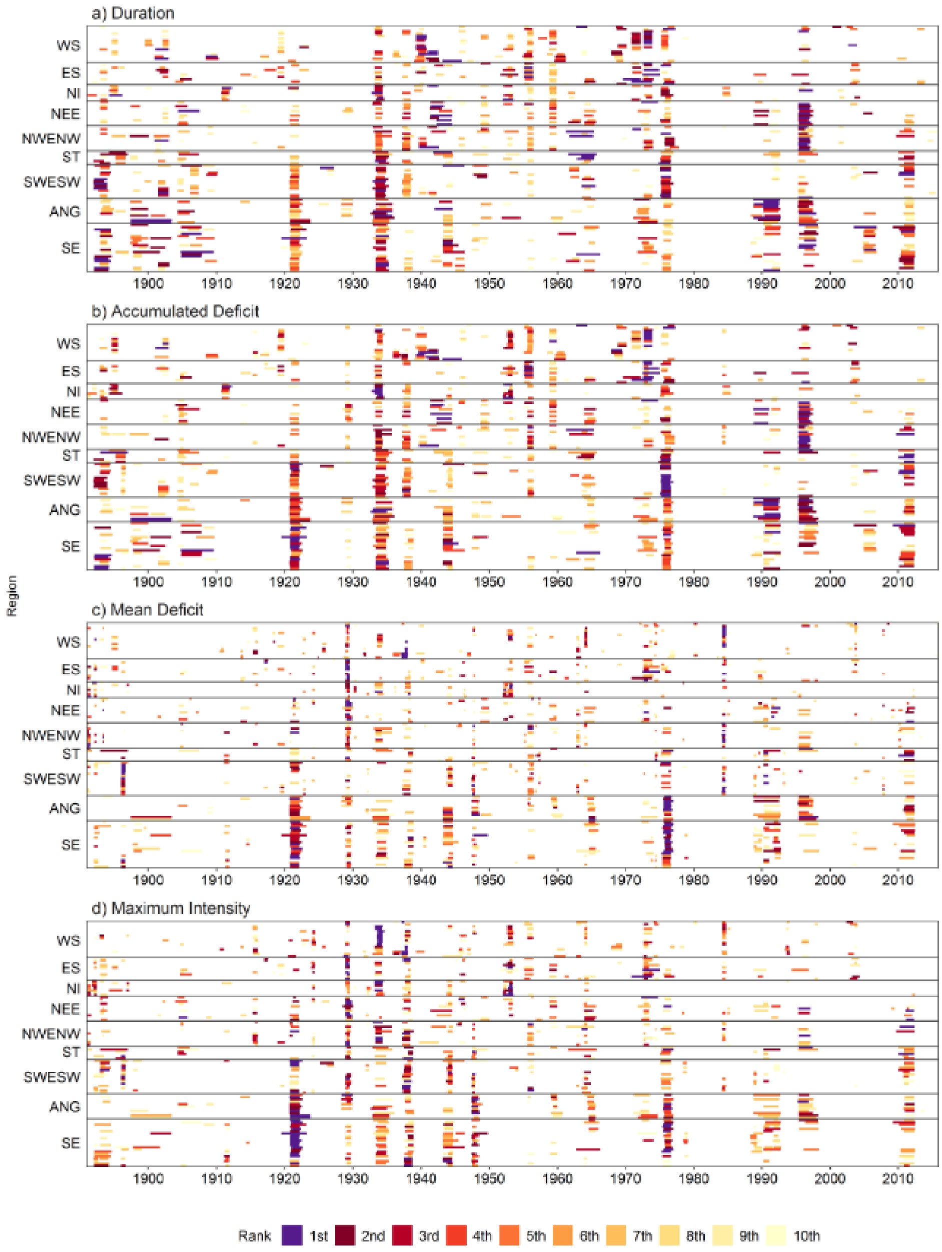


Figure S4 Top 10 extracted events from SSI-3 using a threshold of -1.5 for each drought event characteristic. Catchments are arranged roughly from north to south on the y-axis with each row representing a catchment. Bars represent the top 10 events and are coloured according to the event rank; darker shades represent higher ranking (i.e. more severe) events.

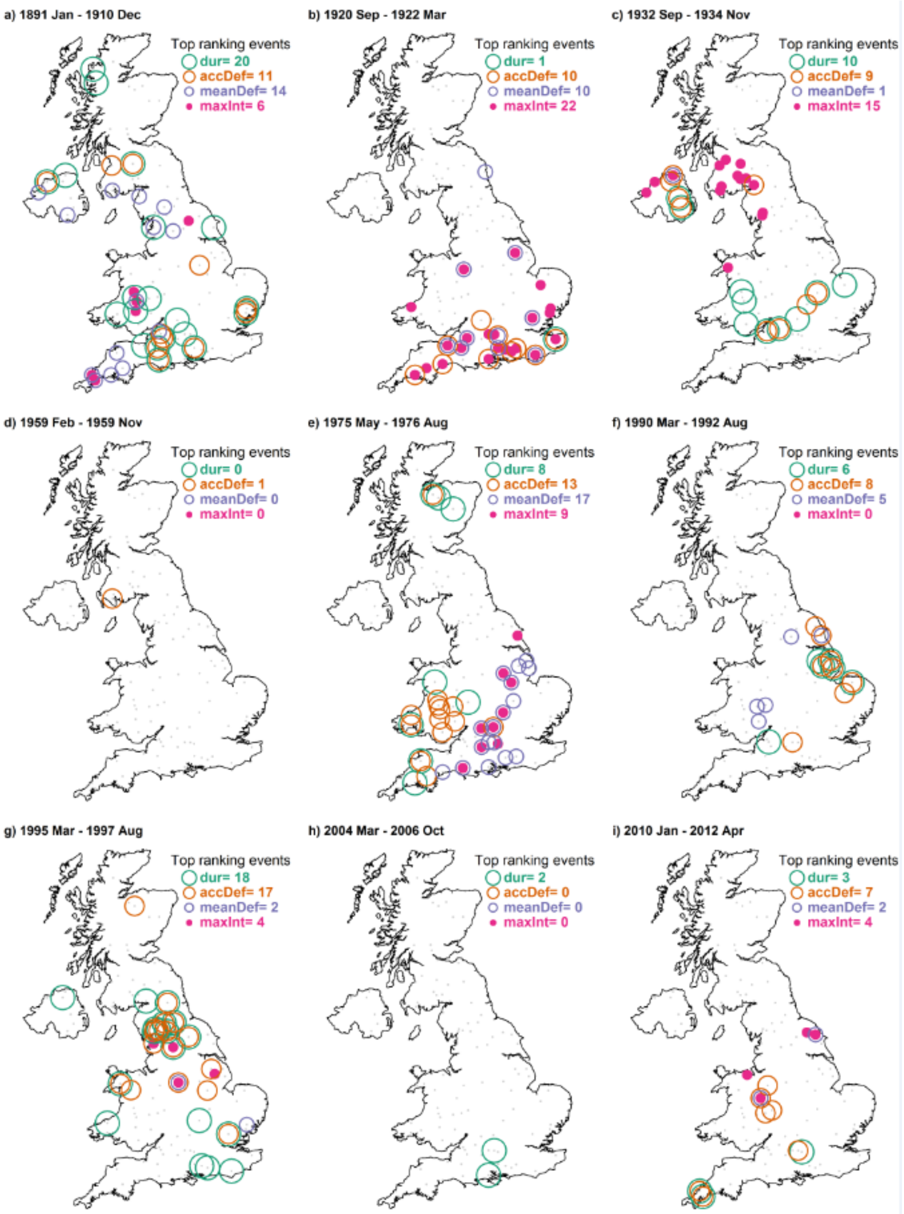


Figure S5 Location and number of LFBN catchments where the top ranking SSI-3 event corresponds to major events (Table 1) for duration (dur), accumulated deficit (accDef), mean deficit (meanDef) and maximum intensity (maxInt). Each of the nine maps represents one of the major drought events listed in Table 1**. Each point on the maps represents the location of the 108 LFBN catchments. Points are coloured pink where the particular event was ranked most severe according to maximum intensity for that catchment. Similarly, points are circled in purple, orange and turquoise to indicate catchments where the particular event was ranked most severe in terms of mean deficit, accumulated deficit and duration, respectively. The numbers in the top right of each map show the number of catchments ranked as most severe for each characteristic for that particular event.**

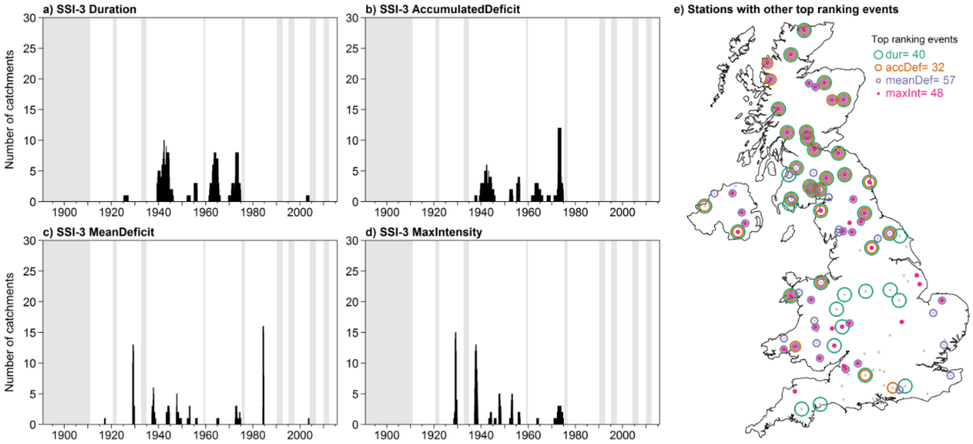


Figure S6 Months when SSI-3 top ranked events occurred outside of the major events (shaded in grey) for the LFBN catchments and each event characteristic (a-d), and e) the location and number of catchments with other top ranking events for each event characteristic. Points are coloured as described in the caption for Figure S5.

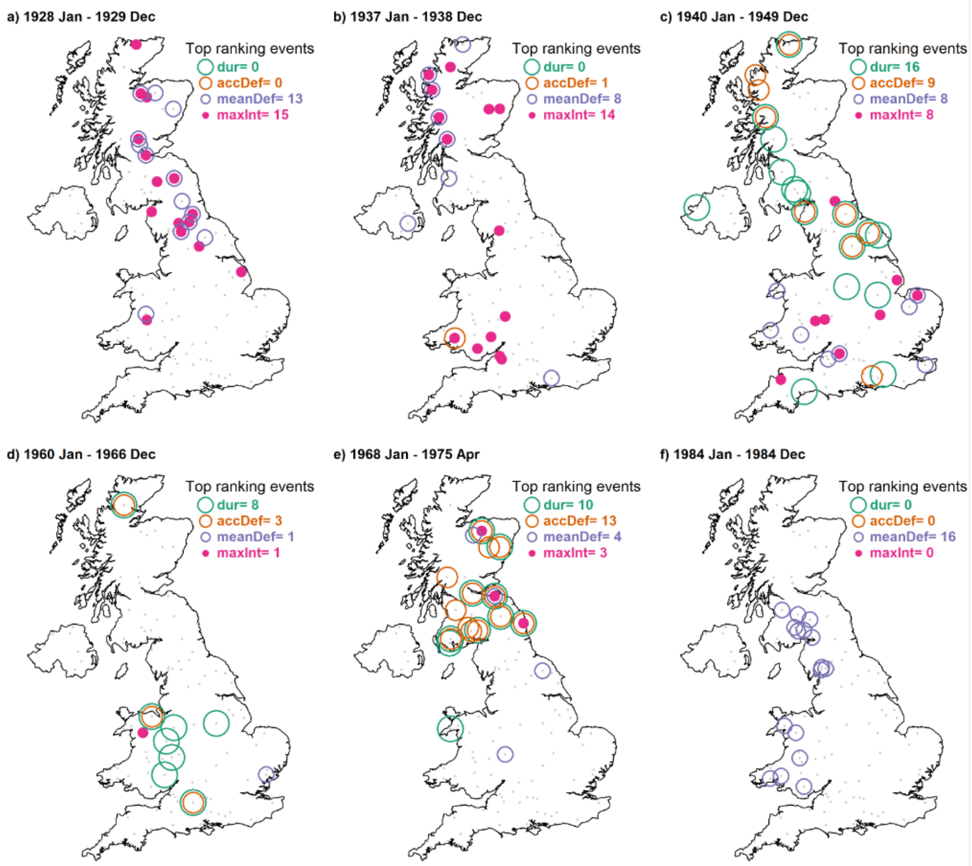


Figure S7 Location and number of LFBN catchments where the top ranking SSI-3 events for each event characteristic occur in periods outside of the major drought events: a) 1928-129, b) 1937-1938, c)1940-1949, d) 1960-1966, e) 1968-1975 and f) 1984. Points are coloured as described in the caption for Figure S5.

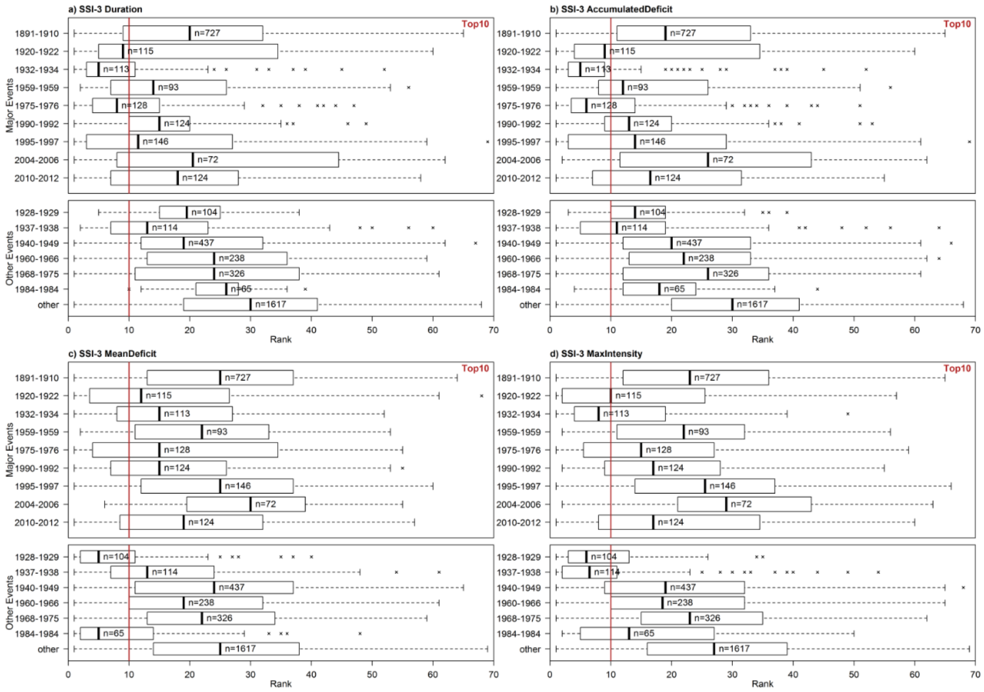


Fig S8 Boxplots showing the ranks of all extracted SSI-3 events where they overlap with the major drought events (top panel for each event characteristic) and identified 'other' events (bottom panel for each event characteristic). Within each box, n refers to the total number of events (across the LFBN) identified that occurred within this period. As multiple events can occur within each given period in individual catchments, it is possible for the value of n to be greater than the number of catchments (i.e. 108).

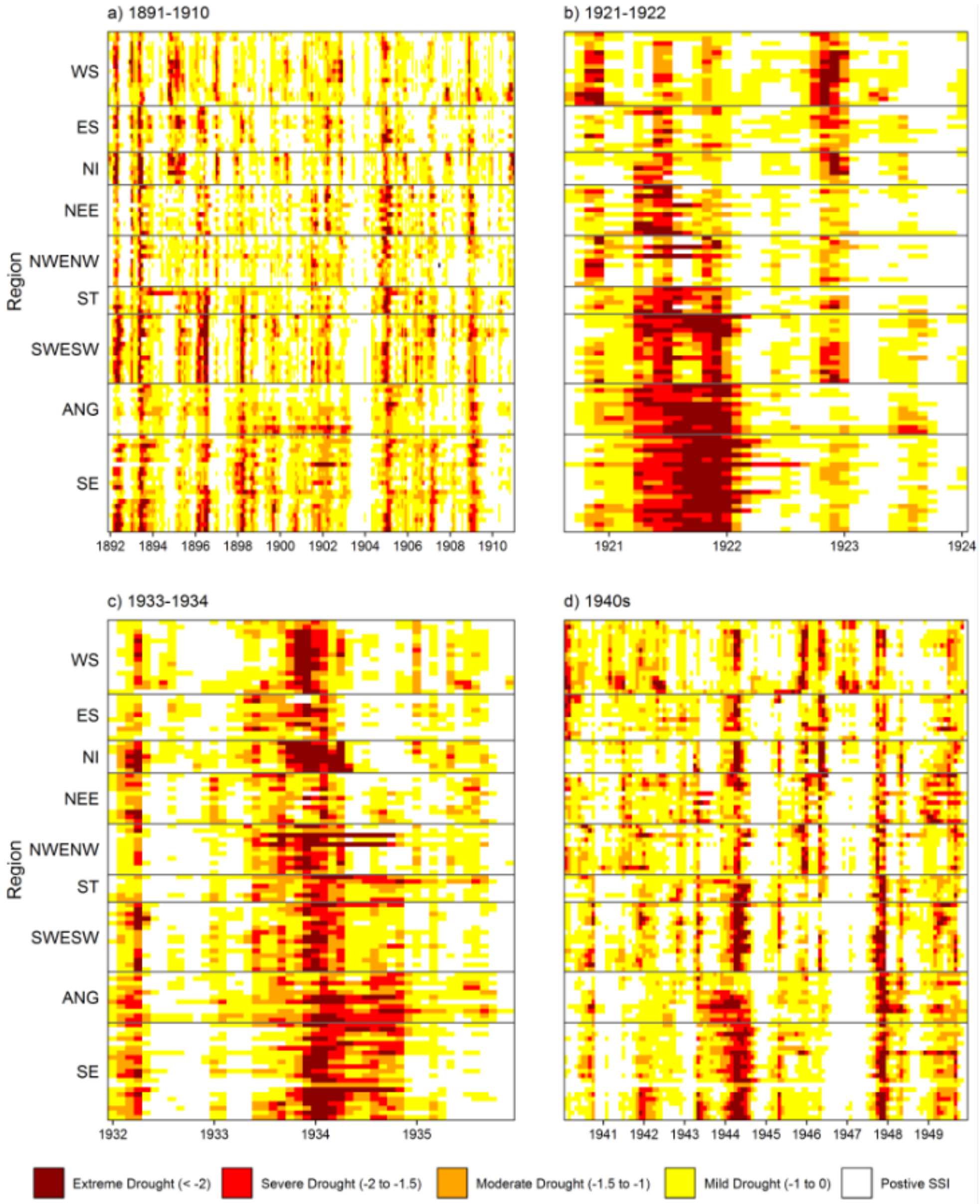


Figure S9 Heat maps of reconstructed SSI-3 for LFBN catchments, arranged roughly from north to south with one row per catchment and regions marked for clarity for a) the 'Long Drought' period (1890s-1910s), b) 1921-1922, c) 1933-1935 and d) the 1940s.

References

National River Flow Archive: https://nrfa.ceh.ac.uk/, last access: 27 September 2019.

Smith, K. A., Tanguy, M., Hannaford, J., and Prudhomme, C.: Historic reconstructions of daily river flow for 303 UK catchments (1891-2015), NERC Environmental Information Data Centre, 10.5285/f710bed1-e564-47bf-b82c-4c2a2fe2810e, 2018.