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Interactive comment on "Historic hydrological droughts 1891–2015: systematic characterisation for a diverse set of catchments across the UK" *by* Lucy J. Barker et al.

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Interactive comment on "Historic hydrological droughts 1891–2015: systematic characterisation for a diverse set of catchments across the UK" by Lucy J. Barker et al.

Anonymous Referee 1
Author Response

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The study is in the scope of HESS. I suggest moderate revisions. Figures could be improved (i.e. more clarity, highlight figure message). All together a valuable contribution to the hydrological community!

We would like to thank the reviewer for the positive feedback on our manuscript and are grateful for the comments on how it can be improved. Here, we respond to each comment in turn, the author responses to each point are given in bold below.

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 will ensure that the citation style is correct in the revised version of the paper.

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 instead of referring to unpublished studies.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 appreciate that we shouldn't cite in preparation/in review papers. The Smith et al., (2019) paper has now been revised and accepted in HESS and the reference will be updated in the revised paper. In regards to Legg McCarthy (in prep) we will remove this 'in preparation' reference and replace it with the references for the finalised data sets (i.e. Met Office 2018, 2019). These datasets have benefitted from additional daily data from ongoing digitisation of daily climatological returns from UK observing stations held in the paper records of the National Meteorological Archives. We feel that citing the catalogued datasets is more appropriate than adding the detail of how data were digitised in this paper. There is a paper in preparation which will sit alongside Met Office (2018) – Hollis et al., however it is still at the 'submission' stage and so it may not be appropriate to cite this paper.

In regards to the modelling, the final version of Smith et al. (2019) assesses the performance of the modelling approach for low flows, and the model has been applied in a range of settings, including the UK – see also response to point C below.

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 feel the results of Smith et al. (2019) demonstrate that GR4J is appropriate for use at low flows for UK catchments. The multi-objective ensemble modelling approach is covered in detail by Smith et al. (2019) and as such is beyond the scope of this paper, however, we will add some more detail on the use of the model for drought and issues of non-stationarity in long-time series to the revised paper. GR4J has also been used across a wide range of flow regimes around the world, has been used for low flow reconstructions (Caillouet et al., 2017), has demonstrated good performance in a diverse set of catchments in the UK (Harrigan et al., 2018), and good performance at simulating temporal transitions between wet and dry periods (Broderick et al., 2016).

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.

Regarding uncertainty - using all 500 model parameterisations from the Smith et al. (2018) dataset was beyond the scope of this study for computational reasons and we acknowledge this in the paper (P25L3) and will further clarify this in the revised paper. However Smith et al. (2019, Figs 9 10) assessed the uncertainty of extracted drought events in the modelled timeseries for nine case study catchments. They found that overall the model results provided accurate

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simulation of drought events, and that uncertainty was higher in the timing of events, whilst estimates of the accumulated deficit were in better agreement. This reinforces the benefit of these data in characterising drought duration, magnitude and intensity.

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.
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.
The following metrics were used by Smith et al., (2019) to assess model performance:

  - **NSE – good at magnitude and timing of peak flows**
  - **LogNSE – NSE on log flows in an attempt to match magnitude and timing of lower flows**
  - **MAPE – overall magnitude of variability**
  - **absPBIAS – total water balance**
  - **MAM30APE – error in the lowest of flows**

– **Q95APE – fitting the tail of the FDC**

These metrics, which although assess performance across the flow regime, have a slight bias towards low flows, but as this is covered in the now revised and accepted Smith et al., (2019) we will continue to direct the reader to this 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?
The paragraph (and subsequent paragraphs) mentioned on P3 already describe the previous assessments of historical droughts in the UK, here we simply introduce that droughts do occur in the UK, however, we will add an exemplar reference to P2L11 in the revised paper.

- P02L20: Is it warm/dry or warm and dry weather?
This should read 'warm and dry' and will be changed in the revised paper.

- P07L04: "end-month"? Is this the same as "right-aligned"?
The SSI is calculated for the end month of the accumulation period, i.e. SSI-3 in December is the SSI for the period October-December. As we have used this terminology previously (e.g. Barker et al., 2016 and Svensson et al., 2017), we will keep this notation but will provide an example for the 3 and 12 accumulation period in the revised paper.

- 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).

To clarify, we removed events with a duration of less than three months (i.e. durations of 1 or 2 months). 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. Drought impacts occur at a range of time scales across the UK (e.g. Bachmair et al. 2016), and we did run the analysis for additional accumulation periods (1, 3, 6, 9, 12, 18 and 24 months) but felt that this was too much information to present in one paper, and so here we selected the 3 and 12 month SSI to broadly represent short and long-term droughts. Results from other accumulation periods can be explored using the UK Hydrological Drought Explorer mentioned on P24L25-26. We will ensure it is clear results for additional accumulation periods can be accessed here too as well as individual catchment results.

- 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? **Gauging stations in the UK are assigned station IDs by the UK National River Flow Archive based on the Hydrometric Area in which the station and catchment falls (for more information see the National River Flow Archive website here: https://nrfa.ceh.ac.uk/station-number and https://nrfa.ceh.ac.uk/hydrometric-areas). The catchments were therefore sorted by station number so they were ordered by region in the following order: Western Scotland, Eastern Scotland, Northern Ireland, North East England, North West England and North Wales, Severn Trent, South West England and South Wales, Anglian and Southern England. Within these regions the indi-**

vidual catchments may not be strictly ordered north to south, but the catchments are in general, therefore ordered by areas that are climatically and physically similar. We appreciate that the catchments could be arranged in a number of ways but we don't think this would add significantly to the interpretation of the figure.

- Fig.4: Are the differences between maximum intensity (dot size) and mean deficit (colors) discussed?
  We will ensure that the differences between maximum intensity (point size) and mean deficit (point colour) are discussed in Section 3.2 in the revised paper.

- 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).
  The Long Drought was indeed a period of many shorter deficits and 1903-1905 was a wet interlude in this prolonged dry period. We explain this in both Section 3.1 and Section 3.4, and we introduce that this period (1890-1910) was called the 'Long Drought' by Marsh et al. (2007) on P2L12.

- 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 would prefer not to separate out the event characteristics to separate maps in Figure 6, but we will add a key to indicate which characteristic relates to which point size and colour, we think that this will make the figure easier to interpret. We will also add this key to the subsequent plots of a

similar style.

- 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?
  The focus of this paper was the drought events identified, characterised and ranked at the catchment scale in a consistent way. MCW2007 did not undertake any systematic quantification of drought magnitude, and so we compared the top ranking events we identified to the major events of MCW2007 e.g. Figure 6. We feel it is beyond the scope of this paper to assess regional-national drought severity/magnitude, and this will be the focus of further works which will assess national/regional drought severity in relation to historic drought impacts.

- 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. However, the exact choice of accumulation period in future studies will depend on the motivation and application of research.

- 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 feel that limitations outlined in Section 4.3 are the key limitations of this study and capture some of the issues related to the modelling approach brought up by the reviewer above. As this section also relates to the next

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steps for this research we feel it is appropriate length, but will endeavour to condense this section in the revised manuscript.

Technical Comments

1. P06L05: Smith et al. (2019) also assessed
   We will change this citation style in the revised paper.
2. P06L09: by Smith et al. (2018)
   We will change this citation style in the revised paper.
3. P06L11: Low Flow Benchmark Network (LFBN).
   We will capitalise Low Flow in the revised paper.
4. P06L17: reconstructed by Smith et al. (2018), which include the LFBN, performed
   We will modify this text as suggested in the revised paper.
5. For readers from outside UK a short explanation of "Anglian" would be helpful (P09L23).
   Anglian region here refers to the Anglian region (ANG) marked on Figure 1 in the paper and on the heatmaps e.g. Figure 3, will refer to this by the region acronym ANG to avoid confusion here.
6. P11L03-04: two times "accumulation period"?
   We will reword this sentence to remove the two mentions of accumulation periods in the revised paper.
7. 7. lower maximum intensity is more severe? (P11L04/05). Terms should be revised here.
   Here we mean 'lower' as more negative which in terms of the maximum

intensity (i.e. the lowest SSI value within the event) would equal a more severe event. We will clarify this in the revised paper.

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?
We will modify the figure so the axis labels are at 90o to the x-axis and will assess what the best way is to make this plot easier to interpret, e.g. by adding vertical lines connecting the points to the x-axis and annotation to mark the observed and pre-observed period as suggested.

9. Remove leading white spaces in (*Figure 5. . .) on page 12.
The white space on page 12 will be removed when the paper is formatted in HESS style following revisions.

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